PATHFINDER

PHYSICAL/CHEMICAL CLOSED LOOP LIFE SUPPORT PROJECT PLAN

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PATHFINDER

Office of Aeronautics and
Space Technology

National Aeronautics and
Space Administration
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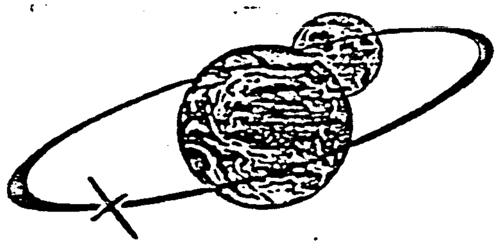
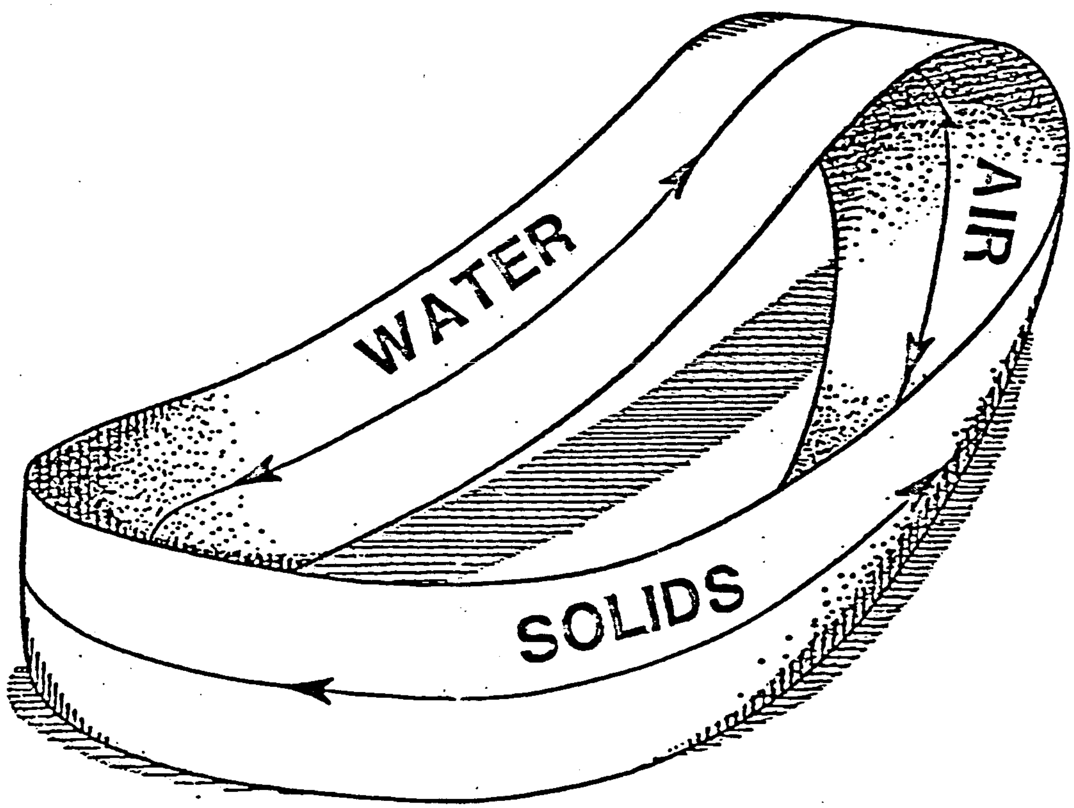


PATHFINDER PROJECT PLAN

Physical/Chemical Closed-Loop Life Support



NASA
Ames Research Center

PROJECT PATHFINDER

Physical/Chemical Closed-Loop Life Support

27 January 1989

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1.0 INTRODUCTION

This document is intended to provide an Agency-wide project plan for advanced Physical/Chemical Closed-Loop Life Support (P/C CLLS) technology development. Its structure is derived from the products of a set of meetings and workshops, sponsored by NASA Headquarters OAST (Code RP) and conducted over a six month period between January and June 1988. **Full development and completion of the plan will require the expertise, considerations and input from representatives of all NASA field centers that have expressed interest in involvement in future life support development, including Ames Research Center (ARC), Johnson Space Center (JSC), Jet Propulsion Laboratory (JPL), Marshall Space Flight Center (MSFC), and Langley Research Center (LaRC).**

NASA is currently studying a broad range of potential human exploration missions, primarily focusing on manned missions to Mars and/or a Lunar Base. New, regenerative life support systems technology will be required to sustain productive human life on whichever missions are selected. Physical/chemical life support is a diverse discipline, encompassing numerous areas of technological and scientific expertise. The intent of the Physical/Chemical Closed-Loop Life Support program is to develop advanced concepts of life support technology for use in the post-Space Station era. Life support systems are necessarily very complex and therefore require the development, integration and control of processes, subsystems and systems which must function within the constraints of mission scenarios and the space environment. Technology is required for supporting entire crews for extended periods; supporting extravehicular systems and the regeneration of portable life support equipment; adaptation to orbital and transit flight; and visits and extended stays on other planets.

1.1 OBJECTIVE OF THIS DOCUMENT

The objective of this five-year project plan is to define the process by which NASA will develop its Physical/Chemical Closed-Loop Life Support (P/C CLLS) systems technology to support human presence beyond the Earth into the Solar System.

Previous human exploration missions have depended upon open-loop life support, i.e. large quantities of life-sustaining expendables including food, water and oxygen have been stored for use during the mission and collected wastes have been returned to earth. Space Station designers are planning to close the oxygen and water loops for the first time, using existing 80's technology. However, long-duration missions such as those planned for the twenty-first century will require advanced, regenerable (closed-loop) systems. Undoubtedly these future missions will make use of both new life support technologies and Space Station concepts and experience to achieve the mix which best meets the needs of each scenario. Technology development of numerous components of Closed-Loop Life Support systems must be accelerated rapidly to mesh with and support U.S. plans for future Solar System exploration

This project plan identifies specific areas of required technology development. It further identifies the objectives for development during the next five years, and specifies the approaches to be taken to achieve them. These approaches include the use of both advanced computational modeling and the more traditional experimental design and subscale-prototype building. For each technology element, the plan presents schedules for FY 89-93, milestones and deliverables, and the required resources. This Project Plan also describes the management approach for integrating, coordinating and achieving the objectives by utilizing the talents of the NASA Centers and external participants, including universities and private industry.

1.2 PROJECT PATHFINDER OVERVIEW

Physical/Chemical Closed-Loop Life Support is a component of Project Pathfinder, a research and technology program that will enable a broad set of space missions and strengthen the technology base of the United States civil space program. Building on the foundation established by the Civil Space Technology Initiative, Project Pathfinder will develop the emerging, innovative technologies that will make possible both new and enhanced human missions, including an intensive study of the Earth, a return to the Moon, piloted missions to Mars and Phobos, and the continuing robotic exploration of the Solar System. Through a strong partnership between NASA and U.S. industry and universities, Project Pathfinder will — as the Apollo program did in the 1960's — push American technology forward, while making future successes in space possible.

Project Pathfinder is organized around four major thrusts: (1) Exploration, (2) Operations, (3) Humans-In-Space, and (4) Transfer Vehicles. Each thrust focuses on a set of key technology elements to support critical mission capabilities. Project Pathfinder will support and interact closely with on-going NASA mission studies.

The Humans-In-Space thrust includes Extravehicular Activity/Suit, Human Performance, and Closed-Loop Life Support. The Closed-Loop Life Support Program will provide technologies that will substantially reduce the mass of consumables and, hence, the cost of resupply for long-duration human space operations. The program will develop and test technologies for closed-loop life support, using both physical/chemical and biologically-based systems. The program will define, develop, and test optimal mixes of the two approaches.

By developing essential technologies, Project Pathfinder will provide the United States with the foundation for long-term leadership in space. It will furnish options for exploration that currently do not exist due to technological limitations and thereby make future successes in space possible. Project Pathfinder will also push American technology forward through a strong partnership between NASA and U.S. industry and universities.

1.3 MISSION STUDIES AND TECHNOLOGY REQUIREMENTS

The goal of NASA's Office of Exploration (OEXP) is to provide the necessary scenarios and viable alternatives for future missions that will allow an early 1990's National decision on a focused program for human exploration of the Solar System. The execution of this goal will result in the following products:

- A long-range plan for exploration and expansion of human presence beyond the Earth and into the Solar System
- A roadmap which provides opportunities and options leading to a commitment to National space exploration initiatives by the year 1992
- A five year plan to identify and foster development and demonstration of the science, technology, and infrastructure critical to the selection of a National space exploration initiative by 1992

The Office of Exploration has developed a process, Figure 1.3-1, that will result in a strategic plan or roadmap defining the best path to follow for human expansion into space. The process begins with the identification of exploration themes, which articulate the rationale for exploration and its importance to the Nation. Through a comprehensive analysis and evaluation process called scenario development, detailed scenarios will be generated defining the systems, technologies, and infrastructures required to execute specific scenarios. This set of scenarios will then be evaluated, judged, and blended to provide a resultant strategic plan. This plan will then become the baseline path for the evolutionary expansion of humans in space.

As the scenarios are developed into proposed missions, technology requirements will become increasingly well defined. One all-encompassing technology requirement depends on the issue of gravity in any given mission. Very early on in Pathfinder, basic assumptions will be required regarding the options of 1-g, low-g or 0-g for specific durations of missions.

Each mission scenario includes technology requirements on issues, including but not limited to: trip duration, level of gravity, crew size, resupply alternatives, power, weight, and/or volume.

These requirements will be translated into closed-loop life support system parameters. These parameters will be dynamic, becoming more well defined as the scenarios reach maturity.

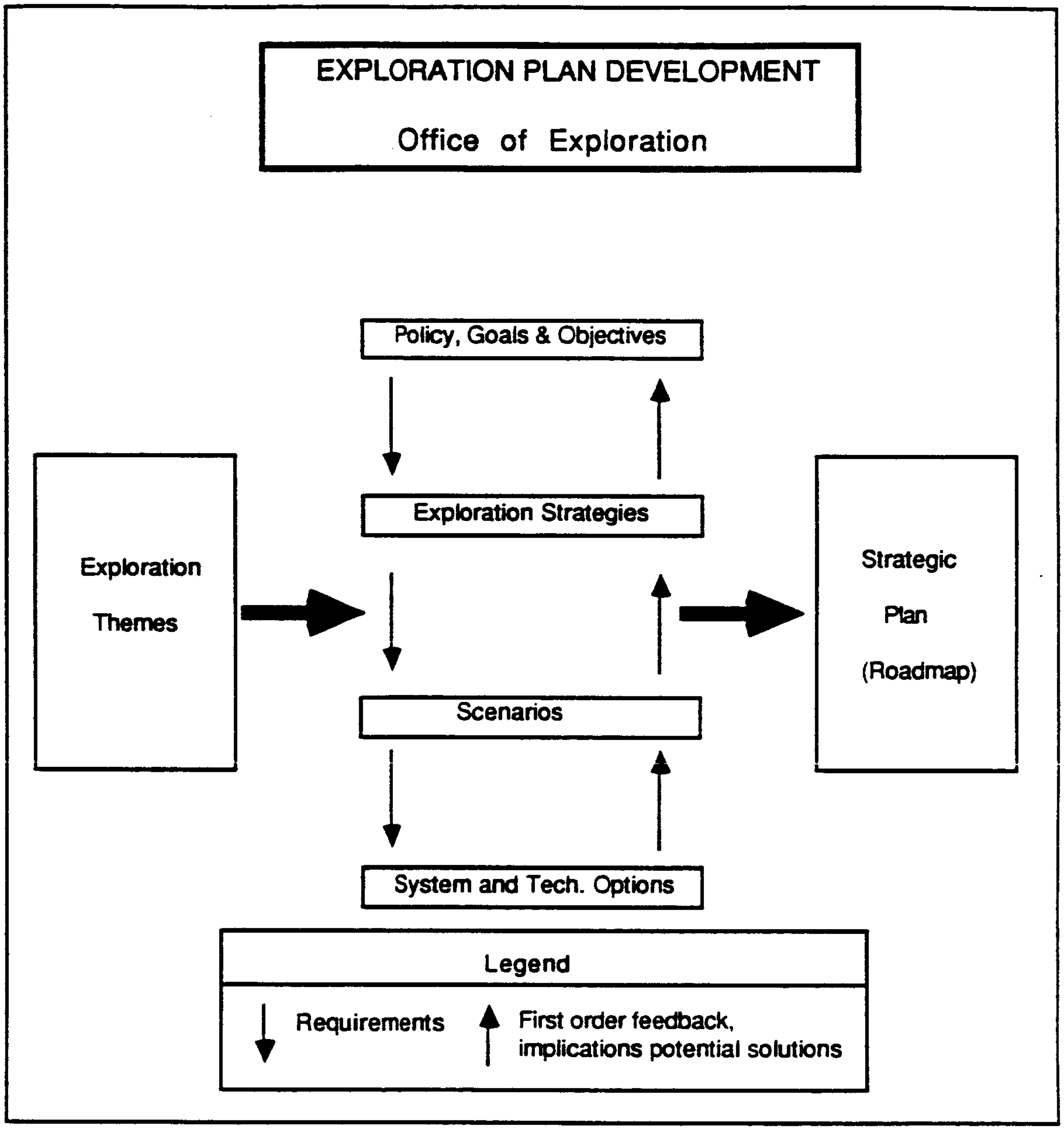


Figure 1.3-1 Exploration Plan Development

1.4 TECHNOLOGY STATUS

Exploration missions designed for the long term presence of humans in a space habitat, e.g., a Lunar base or a mission to Mars, require that a large percentage of their needs be recovered from waste products. (It has been estimated that by efficiently recycling water and air, the resupply costs of life support for the Space Station will be reduced by an order of magnitude.) Cost-effectiveness derived from reduced launch weights for these long missions will only occur if there is a significant improvement in life support systems. The need for reduction in resupply costs for future missions was emphasized in a recent report published by the National Research Council (NRC) (*Space Technology to Meet Future Needs*, National Academy Press, Washington, D.C., 1987).

The NRC report summarizes the status of life support technology in the U.S. and therefore excerpts from that report will be quoted here. It should also be noted that the NRC report, with its emphasis on life support systems design and development, was at least partially responsible for launching the Pathfinder Program.

> "Life support systems for human crew members include maintenance of the environment, especially temperature, pressure and atmospheric content; supply of food and liquids; provisions for personal hygiene; and waste collection and handling." (Environmental temperature and pressure supply were not considered limiting technologies by the NRC and therefore were not discussed in any depth in its review of life support technology.) "Mercury, Gemini, Apollo, and Skylab were the driver missions for supplying consumables from the ground and storing waste in the most practical manner, but none of these missions attempted to close the recovery/recycle loop."

> "Early in the Apollo program it was recognized that the crew's water supply must be sterilized even though it was produced by the reaction of hydrogen and oxygen in the fuel cells; bacteria growth in water storage tanks could not be controlled otherwise. Just as water districts that supply large cities use chlorine, so did Apollo. However, chlorine dissipates quickly and the vehicle's water supply had to be chlorinated on a daily basis. Crew reactions were negative, since the water had a strong chlorine taste and the process required crew action. The lunar module (LM)

was provided with water treated with iodine prior to lift-off, and crews preferred this over chlorinated Apollo command module water."

"Carbon dioxide (CO_2) and odor removal was accomplished with lithium hydroxide (LiOH) canisters, a practical method for a three-man crew and two-week mission."

"Personnel hygiene facilities on Apollo were basic at best. Cleanup was accomplished by wetting cloths and disposing after use in a trash compartment. Waste liquid was pumped directly overboard as generated. Condensate was pumped to a waste tank for storage. A diaper-type device was used for fecal collection, and after use it was stored in a vented waste storage compartment."

"All food continues to be loaded at launch. To correct the potable water problem on Apollo, development work was started on ways to sterilize the supply system without crew involvement. The result, presently installed on Shuttle, is a canister charged with iodine-impregnated resin. This device is called a microbial check valve, because it checks or controls bacteria, not the flowing fluid. The unit has a limited life of three missions and treats only water generated on board the vehicle. Water serviced into the vehicle during ground turnaround is treated with iodine prior to loading. The iodine will plate out on the wall of the storage container, depleting the concentration and resulting in some bacteria in the water, but low enough in count to be acceptable."

"Body waste handling continues to present many problems, although it has improved and is now pumped into a waste tank and stored. The tank is dumped overboard through a heated nozzle if required. Defecate waste is now freeze dried. Recently a vane compactor has been added to increase capacity. CO_2 and odor are still removed by LiOH and charcoal scrubbers."

"The Space Station program will represent the first steps in advancing the state-of-the-art for life support systems. The water loop will be closed by recovery of potable, hygiene, and wash water. Candidate technologies for this recovery include phase change and filtration processes. The CO_2 loop will be closed by either electrochemical, absorption/desorption, or molecular sieve processes. Odor and trace contaminant control will be handled by filtration. However, food will continue to be supplied from the ground, and no recycle of human wastes is planned for the initial phase of the Space Station."

"Little work has been done on processing solid wastes other than compaction, stabilization (by drying or using a biocide), and storage for return to Earth. These approaches are not regenerative. Nothing is recovered from the waste material, not even water."

Since the above-cited NRC Report is almost two years old, the description of the Space Station life support program is not entirely up-to-date. For example, the present design for oder and trace contaminant control is based on the use of filtration, absorption and both high and low-temperature catalysis.

The extent of life support technology development required for future missions is immediately obvious. Technologies actually used for previous human space missions are not regenerative and therefore are incapable of supporting projected long-duration missions. The required closed-loop regenerative systems will emerge only after intensive research and development efforts.

1.5 PROGRAM GOALS AND OBJECTIVES

The primary goal of the Physical/Chemical Closed-Loop Life Support (P/C CLLS) Project is to *provide the technology base required to sustain human life throughout long-duration space missions which will explore the solar system.* For the NASA Ames Research Center (ARC), the secondary goal is to provide agency-wide leadership and coordination for life support and the associated research and technology development activities which compose the project.

The primary goal will be achieved through the combined use of computer modeling and laboratory experimentation. The approach will be applied to the development of technology candidates within the primary elements of a Closed-Loop Life Support (CLLS) system. These elements include (1) water management, (2) solid waste management, (3) air revitalization, and (4) thermal control. Selected aspects of (5) food management will be developed, particularly in areas where the food system impacts any of the other four elements. Analytical techniques will be utilized for the purpose of advancing these five elements, and a large effort will be focused on integrating the subsystems to create a Closed-Loop Life Support system.

Initial objectives for achieving the goals have been identified.

- Develop technology assessments
- Define technology roadmaps which will enable the development of CLLS systems for exploration mission scenarios.
- Identify common as well as mission specific technology requirements.
- Identify and pursue key leverage areas where early research can produce large payoffs.
- Structure the project such that the scope encompasses the range from process development through breadboard and prototype systems development for all components of a CLLS system.
- Develop and provide a validated life support system database.
- Initiate research test facility integration of partially closed-loop life support subsystems.
- Implement P/C and Biological subsystem integration studies.
- Guide a strong university and industrial collaborative program.
- Maintain focus and momentum for the multi-disciplined efforts which will be progressing at the participating NASA centers, and a number of universities and private industries, to insure that the various efforts come together in a supporting and timely fashion.

During the first five years of the Project the primary goal will be to prepare design packages (deliverable) of integrated physical/chemical life support systems for different mission scenarios as defined by OEXP. These packages will contain sufficient design details so that they can be used for the fabrication of breadboard prototype life support subsystems and integrated systems. Design packages of integrated hybrid life support systems which contain biological subsystems (funded by Office of Space Science and Applications) will also be prepared. Optimized designs of automated life support systems will be constructed primarily by analytical methods using validated simulation models. Mass and energy balances will be provided with each design package and the extent of closure will be described. Assumptions used in developing the designs will be clearly stated and recommendations will be made for follow-on research and development. In constructing the design packages, particular attention will be given to including new technologies which may be applicable to a space habitat life support system. The validated models for steady-state and dynamic simulation of the life support systems will also be provided.

Several secondary benefits will accrue to this project during the first five years as a result of developing the design packages. Some of the more important of these secondary benefits are: a) a validated life support systems database, b) expertise in developing relevant steady-state and dynamic models of life support subsystems and integrated systems and c) an orderly approach to the development of life support systems within NASA.

Laboratory experiments will also be carried out during the first five years of the project. The goals of the laboratory experiments will be to assess the feasibility of new processes and to validate process, subsystems, and system models derived from the mission-dependent analytical studies.

The participating NASA R & D centers and the development centers will confer and agree on the format and contents of the life support system design packages. Such an agreement is necessary to insure an orderly transfer of information from the design to the development phase of this project. Similar agreements will be reached on both the design of a life support systems database and the methodology for archiving validated simulation models. The meetings of the Advanced Life Support Intercenter Working Group will provide the forum for discussing and reaching agreement on the foregoing subject (See Section 2.2.2.3).

Technology-specific objectives are presented in detail in Sections 2.4, 2.5 and 2.6 of this project plan.

1.6 TECHNICAL APPROACH

The overall technical approach to be employed in the P/C CLLS project is that of utilizing the appropriate mix of laboratory experimentation and computer modeling for process, subsystem and system analysis. This dual-path approach will receive strong emphasis during the first five years described in this project plan.

Modeling tools will be utilized at three specific levels of P/C CLLS development, the singular process level, the subsystem level (multiple processes), and ultimately for integrated systems (multiple subsystems). In many cases, modeling activities will precede laboratory experimentation and/or testing of a specific process (or subsystem or integrated system). Analytical models will be used as a programmatic tool to screen proposed technologies within a system context so that only technologies with the highest payoff potential are chosen for hardware development, particularly where funding and/or lead time is constrained.

Table 1.6-1 lists the readiness descriptions for technology development of hardware. In general, the Pathfinder Project is expected to progress to technology readiness status #4 - critical function breadboard demonstrated - for the most likely process, subsystem, and integrated system candidates.

Figure 1.6-1 shows the integration of the two development approaches. Throughout the duration of the project, the validation and verification phases of integrating the two development approaches will be crucial for success. The P/C CLLS database will serve as the main repository of the information gathered within each approach. This database will allow ready access to this information by all project personnel.

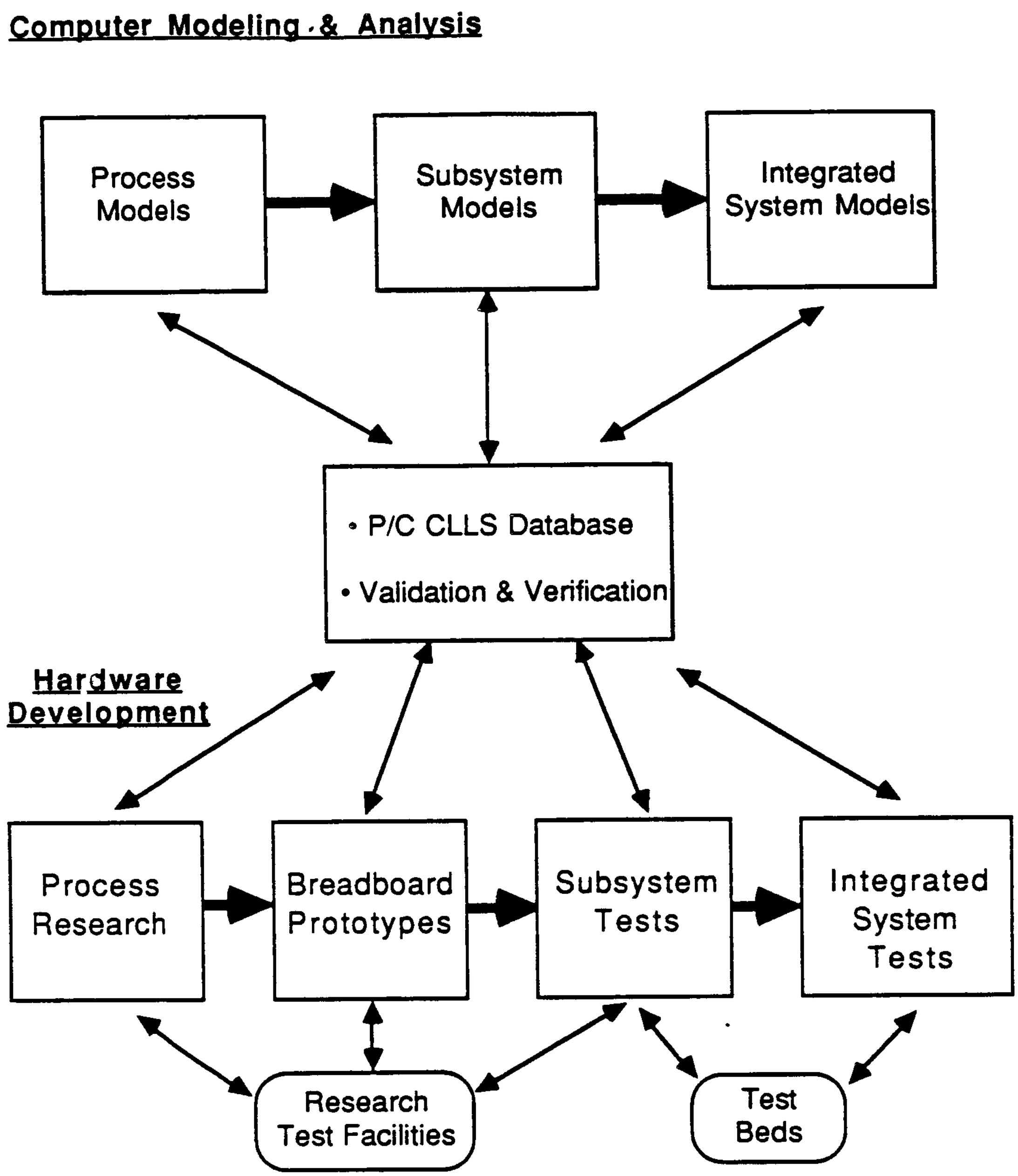


Figure 1.6-1
Integration of Development Approaches

Table 1.6-1
Technology Development
Technology Readiness Status

Status	*Readiness Description*
1	Basic principles observed and reported
2	Conceptual design formulated
3	Conceptual design tested analytically or experimentally
4	Critical function breadboard demonstrated
5	Component tested in relevant environment
6	Subscale system model tested in relevant environment
7	Prototype system model tested in space
8	Baselined into production design

1.7 MANAGEMENT APPROACH

The foremost management philosophy for the Closed Loop Life Support project is that it must be managed from a NASA-wide perspective. The necessary technical and management expertise for this program is currently resident at several NASA centers. Related discipline activities in mission planning, human factors and physiological requirements are also programmatically the responsibility of different NASA Headquarters program offices. To be successful in accomplishing its goals in a timely and cost effective manner in this environment it is absolutely essential that all major project activities have visibility among the participants, full coordination of implementation plans and participation in the implementation process.

The broad technical and management diversity of this project has resulted in the management plan defined in Section 2.2. Many areas of technical knowledge and expertise throughout the Agency must contribute to the project in a management structure that assures full integration of the efforts while allowing for the lowest level of management decision-making feasible. To assure the functioning of the management system, clean lines of authority and reporting have been established. In addition, considerable effort has been expended to define clear areas of responsibility for project implementation. While difficult to negotiate, the assignment of well-defined lead and supporting roles to the participating centers should contribute to the smooth functioning of the management process. The lead center concept by WBS element should assure decision-making latitude at the lowest possible level while retaining appropriate management accountability for accomplishment.

Another critical element of the management plan is the emphasis placed on technical coordination among the project elements. Communication forums and mechanisms will be provided to assure the rapid dissemination of technical developments, capitalization of research findings and technology development and the elimination of redundant activities or unnecessary overlaps in the project tasks.

The management structure will also focus on the priority issue of technology transfer. The ultimate success of this project will in large part be judged on the impact the newly developed technologies have on the future exploration programs implemented from Project Pathfinder. Technology transfer is unlikely to occur unless management takes this goal seriously and provides an environment and culture that encourages migration of ideas from the laboratory to actual applications. Not only must we develop "good" ideas, we must also act to insure that team-building occurs across discipline and organizational lines to insure transfer. This team-building is most important between the research and development centers. The planned management structure has established the appropriate goals and plans to make this happen but only time and follow-through will develop the mutual respect and confidence necessary to assure its occurrence.

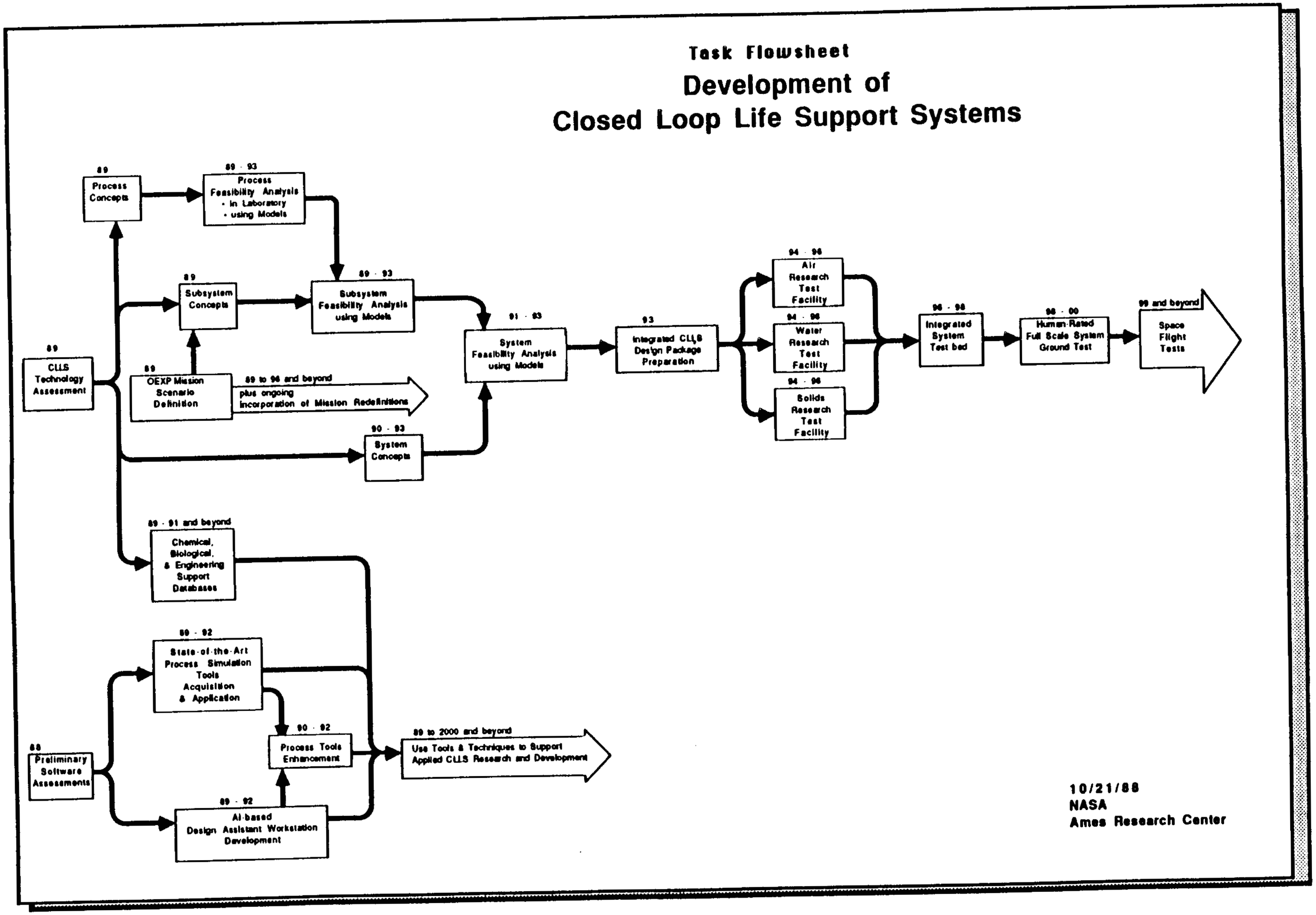
1.8 PROJECT SCHEDULE

Work in the five year period between 1989 and 1993 will focus upon CLLS technology assessment. Initially, various process level technologies will be examined, with this work evolving towards modeling studies and trade offs at the subsystem and system levels. The end product of this five year activity will be the delivery of integrated CLLS design packages. These design packages will contain detailed analytical presentations of alternative CLLS system designs suitable for supporting various Lunar and Mars missions.

1994 and beyond will see a major transition toward systems development using ground test beds. Initially, research test facilities will be used to evaluate CLLS design packages at the air, water, and waste subsystem levels. Beginning in 1996, this work will be integrated, resulting in an integrated CLLS system test bed. Human-rated system tests and flight tests are projected to follow in 1998 and beyond.

Concurrent with the above activities will be continuous exploratory research into new technologies. Some base level of database and modeling support will also be provided throughout the program.

A graphical task flowsheet presenting the evolutionary development of the CLLS Project is shown in Figure 1.8-1.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• using Models
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Subsystem Concepts
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89
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plus ongoing incorporation of Mission Redefinitions
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90 - 93
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93
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98 - 00
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99 and beyond
Space Flight Tests
89 - 91 and beyond
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Figure 1.8-1

2.0 PROGRAM DESCRIPTION

2.1 WORK BREAKDOWN STRUCTURE

The Work Breakdown Structure (WBS) for the Physical/Chemical Closed-Loop Life Support Project is outlined below. The project is divided into four technical sections: 1.1 Physical/Chemical Life Support, 1.2 Portable Life Support Systems, 1.3 Systems Control, and 1.4 System Integration. Each technical section is sub-divided further into two to six elements (3-digit level, 1.1.1, 1.1.2, etc.). Each of these elements is then broken-down into two to nine sub-elements (4-digit level, 1.1.1.1, 1.1.1.2, etc.). Portable Life Support Systems (Technical Section 1.2) are covered in a separate document, EVA/Suit Project Plan.

1.0 CLOSED LOOP LIFE SUPPORT

1.1 PHYSICAL/CHEMICAL LIFE SUPPORT

1.1.1 Thermal Control
- 1.1.1.1 Heat Acquisition
- 1.1.1.2 Heat Transport
- 1.1.1.3 Heat Rejection
- 1.1.1.4 Heat Storage
- 1.1.1.5 Subsystem and System Analysis
- 1.1.1.6 Subsystem Test

1.1.2 Air Revitalization
- 1.1.2.1 Temperature and Humidity Control
- 1.1.2.2 Gas Composition and Pressure Control
- 1.1.2.3 Trace Contaminant Control
- 1.1.2.4 CO_2 Removal and Reduction
- 1.1.2.5 O_2, N_2, H_2 Supply
- 1.1.2.6 In-situ Resources
- 1.1.2.7 Subsystem and System Analysis
- 1.1.2.8 Subsystem Test
- 1.1.2.9 Plant Interface

1.1.3 Water Management
- 1.1.3.1 Water Processing Technology
- 1.1.3.2 Plant Interfaces
- 1.1.3.3 In-situ Resources
- 1.1.3.4 Subsystem and System Analysis
- 1.1.3.5 Subsystem Test

1.1.4 Solid Waste Management
- 1.1.4.1 Waste Composition and Definition
- 1.1.4.2 Waste Handling and Processing
- 1.1.4.3 Product Recycling
- 1.1.4.4 Subsystem and System Analysis
- 1.1.4.5 Subsystem Test
- 1.1.4.6 Plant Interface

1.1.5 Food Management
- 1.1.5.1 Dietary Logistics
- 1.1.5.2 Food Synthesis
- 1.1.5.3 Processing Technology
- 1.1.5.4 In-situ Resources
- 1.1.5.5 Subsystem and System Analysis
- 1.1.5.6 Subsystem Test

1.2 PORTABLE LIFE SUPPORT SYSTEMS (Shown for reference only)

1.2.1 Thermal Control Systems
- 1.2.1.1 Subsystem Analytical Modeling
- 1.2.1.2 Heat Storage
- 1.2.1.3 Heat Acquisition
- 1.2.1.4 Heat Transport
- 1.2.1.5 Heat Rejection
- 1.2.1.6 Subsystem Test

1.2.2 Atmosphere Control
- 1.2.2.1 Subsystem Analytical Modeling
- 1.2.2.2 O_2 Supply
- 1.2.2.3 CO_2 Control
- 1.2.2.4 Trace Contaminant Control
- 1.2.2.5 Humidity Control
- 1.2.2.6 Subsystem Test

1.2.3 Monitoring and Control
- 1.2.3.1 Subsystem Analytical Modeling
- 1.2.3.2 Automated Control Technology
- 1.2.3.3 Display Technology
- 1.2.3.4 Subsystem Test

1.2.4 System Integration
- 1.2.4.1 Requirements
- 1.2.4.2 Analysis
- 1.2.4.3 Support Equipment and Interfaces

1.3 SYSTEMS CONTROL

1.3.1 Systems Monitoring & Control Instrumentation
- 1.3.1.1 Integration
- 1.3.1.2 Food
- 1.3.1.3 Biological Contamination

1.3.2 Systems Control Strategy
- 1.3.2.1 Autonomous Control
- 1.3.2.2 "Semi-Autonomous" Control

1.4 SYSTEM INTEGRATION

1.4.1 System Requirements
- 1.4.1.1 Baseline Requirements
- 1.4.1.2 Lunar Base
- 1.4.1.3 Mars Sprint
- 1.4.1.4 Mars Base

1.4.2 P/C Bio Systems
- 1.4.2.1 Concepts/Integration Analysis
- 1.4.2.2 Integration Requirements
- 1.4.2.3 Control

1.4.3 System Analysis and Assessment
- 1.4.3.1 Analytical Techniques
- 1.4.3.2 Technology Assessment
- 1.4.3.3 Payoff/Trade-off Assessment
- 1.4.3.4 Optimization Studies
- 1.4.4.5 Logistics Analysis
- 1.4.3.6 Performance Predictions
- 1.4.3.7 Information Transfer

1.4.4 Validation and Verification
- 1.4.4.1 Ground Test Data
- 1.4.4.2 Flight Test Data

1.4.5 System Tests
- 1.4.5.1 Requirements
- 1.4.5.2 Test Facility Reviews
- 1.4.5.3 Flight Experiments

1.4.6 Human-Rated Tests
- 1.4.6.1 Requirements
- 1.4.6.2 Ground Test Bed
- 1.4.6.3 Flight Experiments

2.2 MANAGEMENT PLAN

The approach to managing the Physical/Chemical Closed-Loop Life Support project is outlined in Section 1.7 of this project plan. Details of the management plan itself are described in the following subsections which cover the basic aspects of management structure, project coordination, project planning and program reporting. A single, central Research and Technology Objectives and Plans (RTOP) document will be prepared for the project. Work elements for the RTOP document will be provided by the individual participating NASA centers as appropriate.

2.2.1 Management Structure

2.2.1.1 NASA Headquarters

P/C CLLS management responsibilities will be maintained by the Propulsion, Power, and Energy Division (Code RP), within the Office of Aeronautics and Space Technology (OAST) at NASA HQ. A P/C CLLS Program Manager will be assigned by Code RP. Figure 2.2.1-1 depicts the management structure for the program. This figure includes the advisory review roles filled by NASA HQ Codes EB and RC, and by proposed external review committees.

2.2.1.2 NASA Ames Research Center

As illustrated in Figure 2.2.1-1 the lead center for development and implementation of the P/C CLLS Project is ARC. A P/C CLLS Project Manager (PM) will be assigned by ARC. This PM will have the responsibility for overall project administration including technical planning; maintaining and reporting schedules and milestones; planning, disbursement and tracking of resources; and facility and staff planning. The PM will be responsible for coordinating and integrating the P/C CLLS work of all participating centers, universities and private industry. The PM will have the authority to resolve conflicts within the project.

Figure 2.2.1-2 shows the proposed structure for Closed-Loop Life Support activities at Ames. ARC will establish a Life Support Systems Services (LS^3) contract to supplement civil service staff in many functions of project implementation. A Request For Proposals will be announced, and award of the contract will be made through the Ames Procurement Division. The on-site contractors will work in the areas of project administration and research and technology development. Contracting plans are discussed further in Section 3.0 of this project plan.

PHYSICAL/CHEMICAL CLOSED-LOOP LIFE SUPPORT PROGRAM MANAGEMENT STRUCTURE

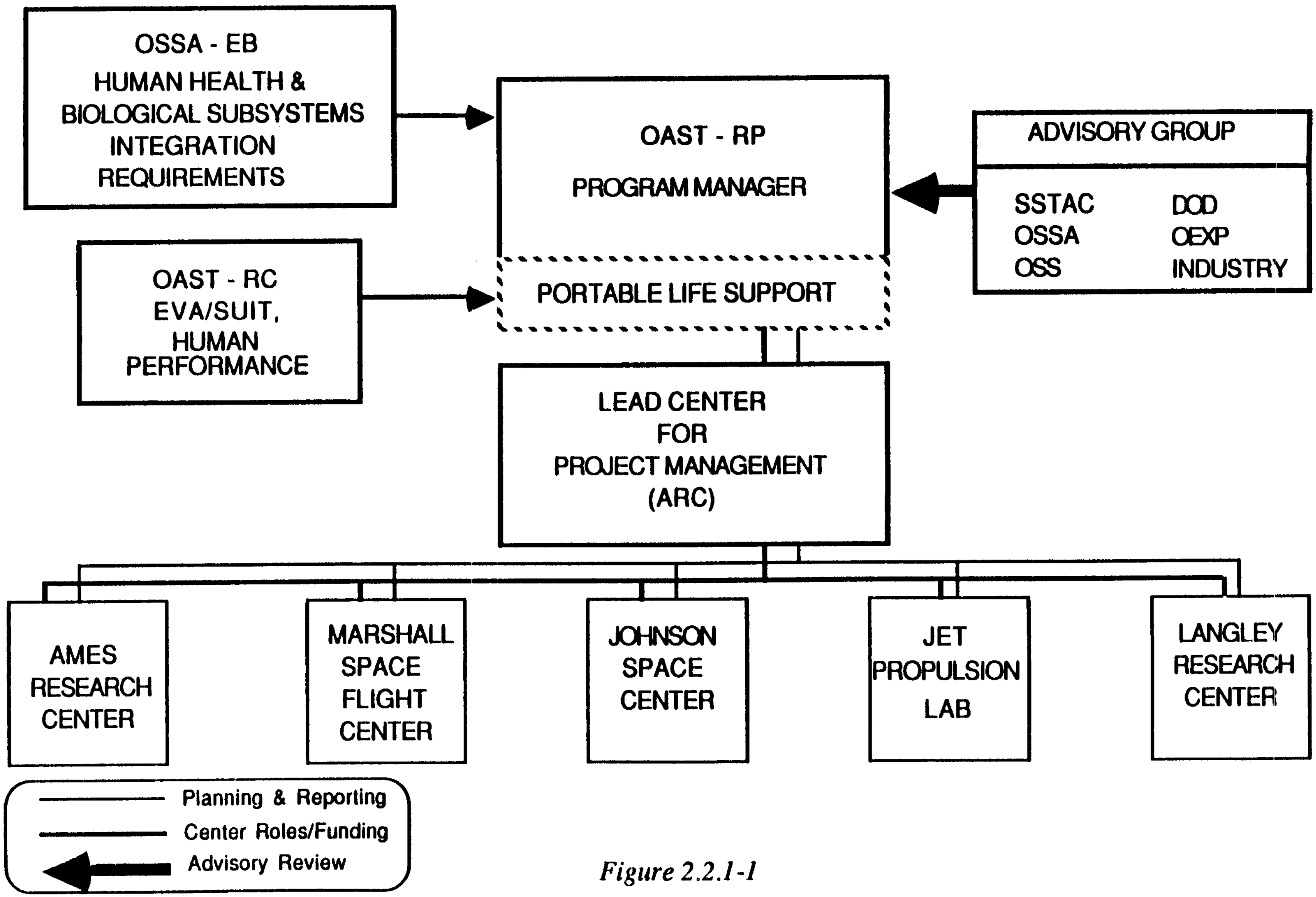


Figure 2.2.1-1

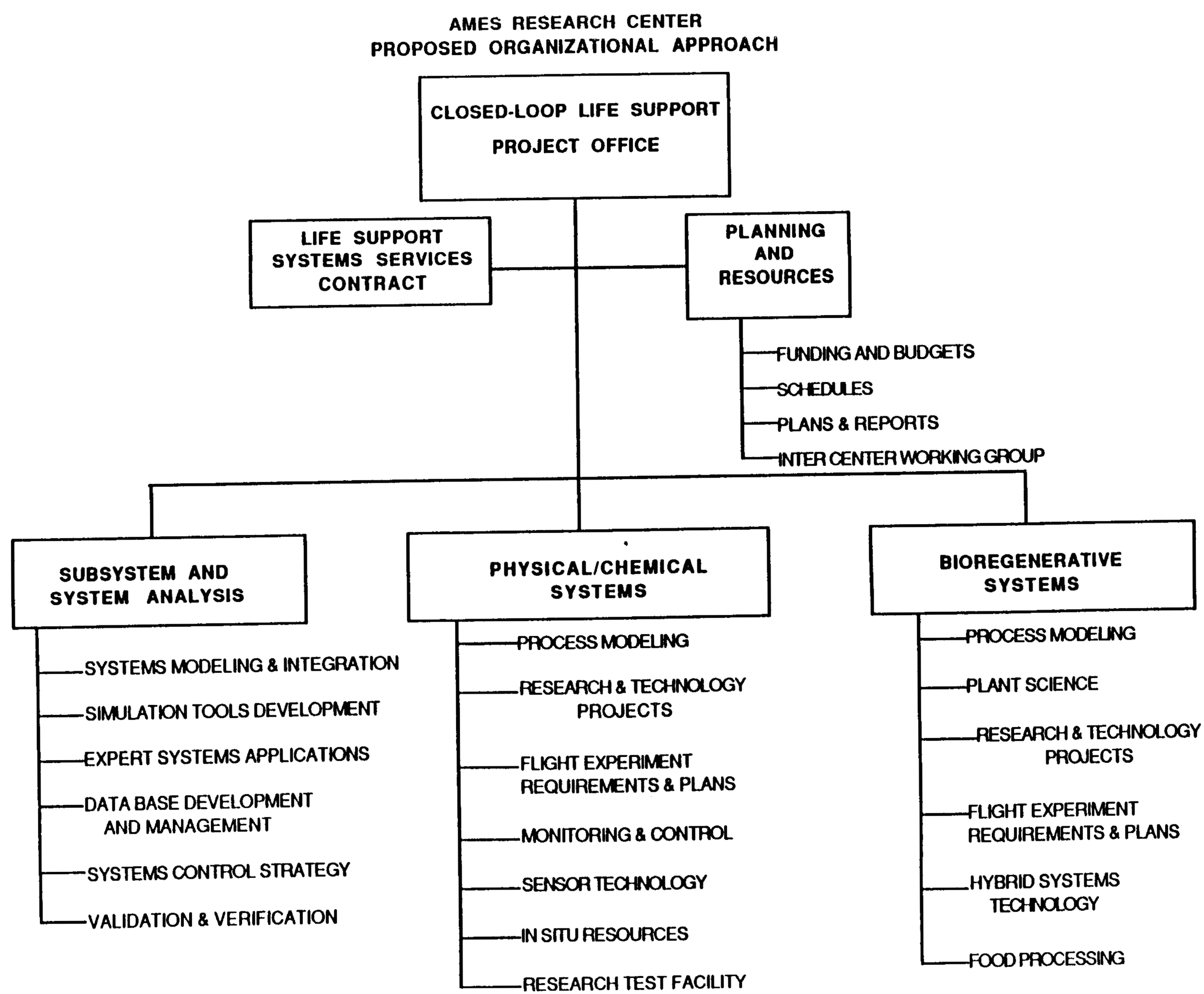

AMES RESEARCH CENTER
PROPOSED ORGANIZATIONAL APPROACH
CLOSED-LOOP LIFE SUPPORT
PROJECT OFFICE
LIFE SUPPORT
SYSTEMS SERVICES
CONTRACT
PLANNING
AND
RESOURCES
FUNDING AND BUDGETS
SCHEDULES
PLANS & REPORTS
INTER CENTER WORKING GROUP
SUBSYSTEM AND
SYSTEM ANALYSIS
SYSTEMS MODELING & INTEGRATION
SIMULATION TOOLS DEVELOPMENT
EXPERT SYSTEMS APPLICATIONS
DATA BASE DEVELOPMENT
AND MANAGEMENT
SYSTEMS CONTROL STRATEGY
VALIDATION & VERIFICATION
PHYSICAL/CHEMICAL
SYSTEMS
PROCESS MODELING
RESEARCH & TECHNOLOGY
PROJECTS
FLIGHT EXPERIMENT
REQUIREMENTS & PLANS
MONITORING & CONTROL
SENSOR TECHNOLOGY
IN SITU RESOURCES
RESEARCH TEST FACILITY
BIOREGENERATIVE
SYSTEMS
PROCESS MODELING
PLANT SCIENCE
RESEARCH & TECHNOLOGY
PROJECTS
FLIGHT EXPERIMENT
REQUIREMENTS & PLANS
HYBRID SYSTEMS
TECHNOLOGY
FOOD PROCESSING

Figure 2.2.1-2

2.2.1.3 Participating Centers

Participating centers currently include Ames Research Center (ARC), Jet Propulsion Laboratory (JPL), Johnson Space Center (JSC), Langley Research Center (LaRC), and Marshall Space Flight Center (MSFC).

All participating centers will assign a P/C CLLS Technical Manager (TM) to serve as a focal point for that center. The P/C CLLS Technical Managers at participating centers will be responsible to the ARC PM for completion of project responsibilities and utilization of financial resources assigned. The participating centers will be responsible to the ARC PM for all administrative matters pertaining to reporting and review requirements.

For each technical element within the project, participating NASA centers will be designated either as the lead center or a support center. Lead centers will have the responsibility of planning the work to be performed within each element. The lead center will coordinate the research and development work among themselves and the support centers for the element and monitor the progress within the element. The support centers will perform research and technology development on sub-elements within a given element. The support centers will cooperate with the lead center for each element. Participation over the five year period in some elements is yet to be determined for some centers.

CENTER ROLES

Assignments of center roles for each of the technical elements within the project are listed in Table 2.2.1-1.

AMES RESEARCH CENTER (ARC)

In addition to its responsibility for project management, ARC will serve as the lead center for the technical elements dealing with Water Management, Solid Waste Management, Systems Control Strategy, P/C Bio Systems, Systems Analysis and Assessment, Validation and Verification and System Tests. ARC will take the lead in developing and/or assembling modeling and analytical tools useful for the design of new systems. ARC will focus its research and technology efforts on revolutionary concepts or new devices and systems which will replace present/previous technology. Also, ARC will serve as a support center for those technical elements where other centers have the lead role.

JET PROPULSION LABORATORY (JPL)

JPL will serve as a support center for the Air Revitalization, Water Management, Solid Waste Management, System Requirements, P/C Bio Systems, and System Analysis and Assessment elements.

JOHNSON SPACE CENTER (JSC)

JSC will be the lead center for the Thermal Control, Air Revitalization, and Food Management elements. These elements are areas in which JSC has long-standing expertise. JSC will also serve as the lead center for the System Requirements and Human-Rated Tests elements. Finally, JSC will serve as a support center for the elements involving Water Management, Solid Waste Management, Systems Analysis and Assessment, Validation and Verification, and System Tests.

JSC, as the Special Assessment Agent (SAA) for life support for the NASA Office of Exploration (OEXP), will serve as the continuing interface between the P/C CLLS project and OEXP in the area of life support. This interface will be of prime importance in JSC's lead role for the System Requirements element.

LANGLEY RESEARCH CENTER (LaRC)

LaRC will serve as a support center for the Systems Analysis and Assessment element with emphasis on top level systems modeling for payoff/trade-off assessments.

MARSHALL SPACE FLIGHT CENTER (MSFC)

MSFC will serve as the lead center for the Systems Monitoring and Control Instrumentation element as a means of extending Space Station technology in this area to the next generation of life support systems. MSFC will further contribute to this extension of Space Station technology by providing support for all of the Physical/Chemical Life Support Elements (WBS Level 1.1). Finally, MSFC will also serve as a support center for the Systems Control Strategy, Systems Analysis and Assessment, Validation and Verification, System Tests and Human-Rated Tests elements.

Table 2.2.1-1 NASA Center Roles — P/C CLLS

	ARC	JPL	JSC	LaRC	MSFC
1.1 PHYSICAL/CHEMICAL LIFE SUPPORT					
1.1.1 Thermal Control	S		L		S
1.1.2 Air Revitalization	S	S	L		S
1.1.3 Water Management	L	S	S		S
1.1.4 Solid Waste Management	L	S	S		S
1.1.5 Food Management	S		L		S
1.2 PORTABLE LIFE SUPPORT SYSTEMS					
1.2.1 Thermal Control Systems	SEE EVA/SUIT				
1.2.2 Atmosphere Control	PROJECT PLAN				
1.2.3 Monitoring & Control	FOR DETAILS				
1.2.4 System Integration					
1.3 SYSTEMS CONTROL					
1.3.1 Systems Monitoring & Control Instr.	S				L
1.3.2 Systems Control Strategy	L				S
1.4 SYSTEM INTEGRATION					
1.4.1 System Requirements	S	S	L		
1.4.2 P/C Bio Systems	L	S			
1.4.3 Systems Analysis & Assessment	L	S	S	S	S
1.4.4 Validation & Verification	L		S		S
1.4.5 System Tests	L		S		S
1.4.6 Human-Rated Tests	S		L		S

L = *Lead Center*
S = *Support Center*

2.2.2 Project Coordination

2.2.2.1 NASA Headquarters

The P/C CLLS project will be closely coordinated by the OAST with the Office of Space Science and Applications (OSSA) and the Office of Exploration (OEXP). OSSA will be responsible for establishing human health and biological subsystems integration requirements as guidance to the development of physical/chemical technologies. OEXP will provide mission scenario developments to the program upon which the development of technologies will be based. The status of Space Station life support will also be assessed periodically in cooperation with the Office of Space Station to ascertain the state-of-the-art in life support flight systems.

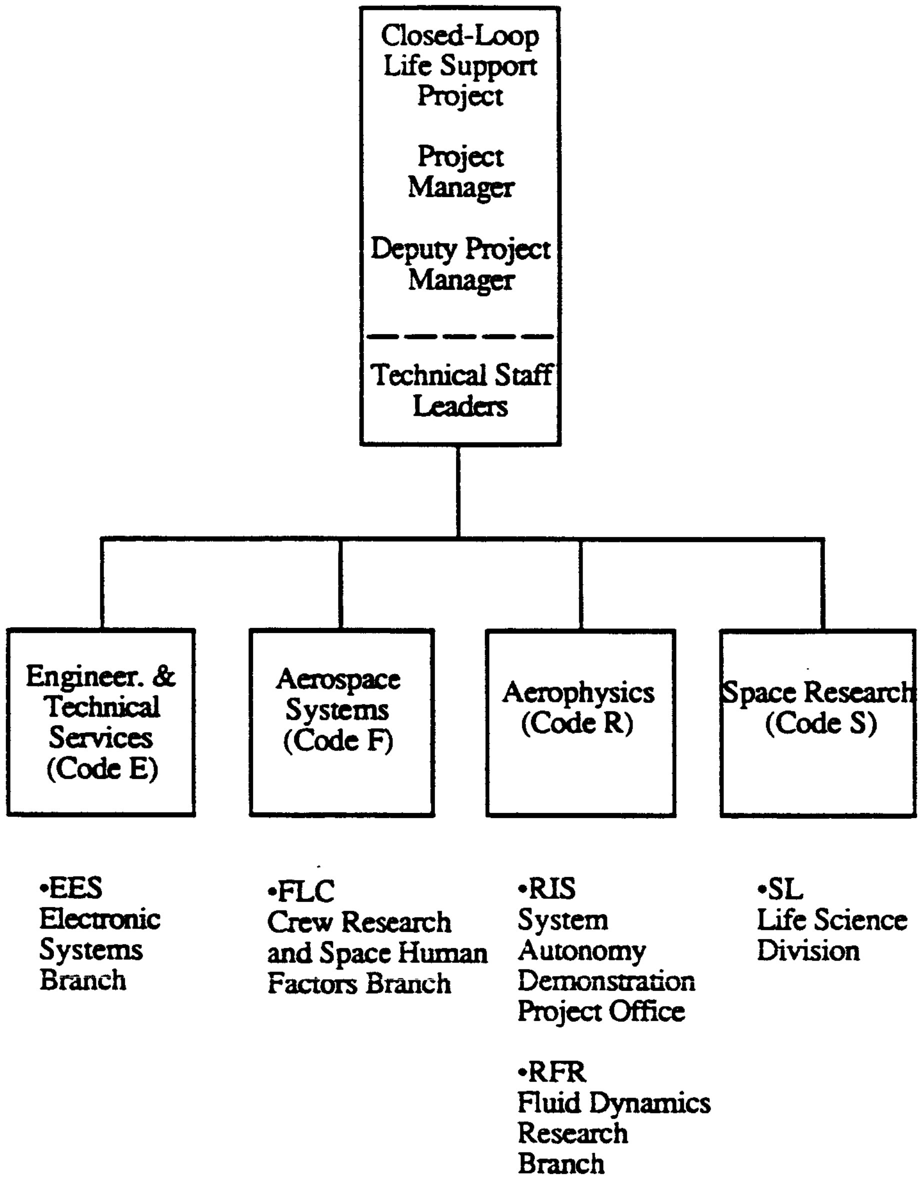
Within OAST, coordination will be maintained with all relevant Base R & T programs in areas applicable to life support and thermal control technologies, and with the Code RC Program Managers for EVA/Suit and Human Performance in the area of portable life support systems for extravehicular activity. Coordination will also be maintained with Code RM vis-a-vis the Resource Processing Pilot Plant element of Pathfinder in regard to utilization of in-situ resources for life support systems.

Secondary coordination will be established and maintained with the Department of Defense, specifically the U.S. Army, Air Force, and Navy for the exchange of information and technology in areas common with NASA's Life Support program.

2.2.2.2 Ames Research Center

The P/C CLLS project requires skills in many diverse technical areas. An organization is required which provides the diverse talents to the project. Full coordination, cooperation, and support will be maintained among the Ames Research Center's Code E, Engineering and Technical Services Directorate; Code F, Aerospace Systems Directorate; Code R, Aerophysics Directorate; and Code S, Space Research Directorate.

Figure 2.2.2-1 illustrates the Division and Branch Offices within these Directorates which support the project. Figure 2.2.2-2 shows the expected participation of these Divisions and Branches in the work to be performed for each technical element in the WBS. Each Division or Branch Office will provide management and administrative support for those technical elements where there is a significant involvement of the Division or Branch technical staff. The respective Division and Branch Chiefs will confer with the ARC PM and reach agreements on the necessary level of this support.



Ames Research Center Support Elements

Figure 2.2.2-1

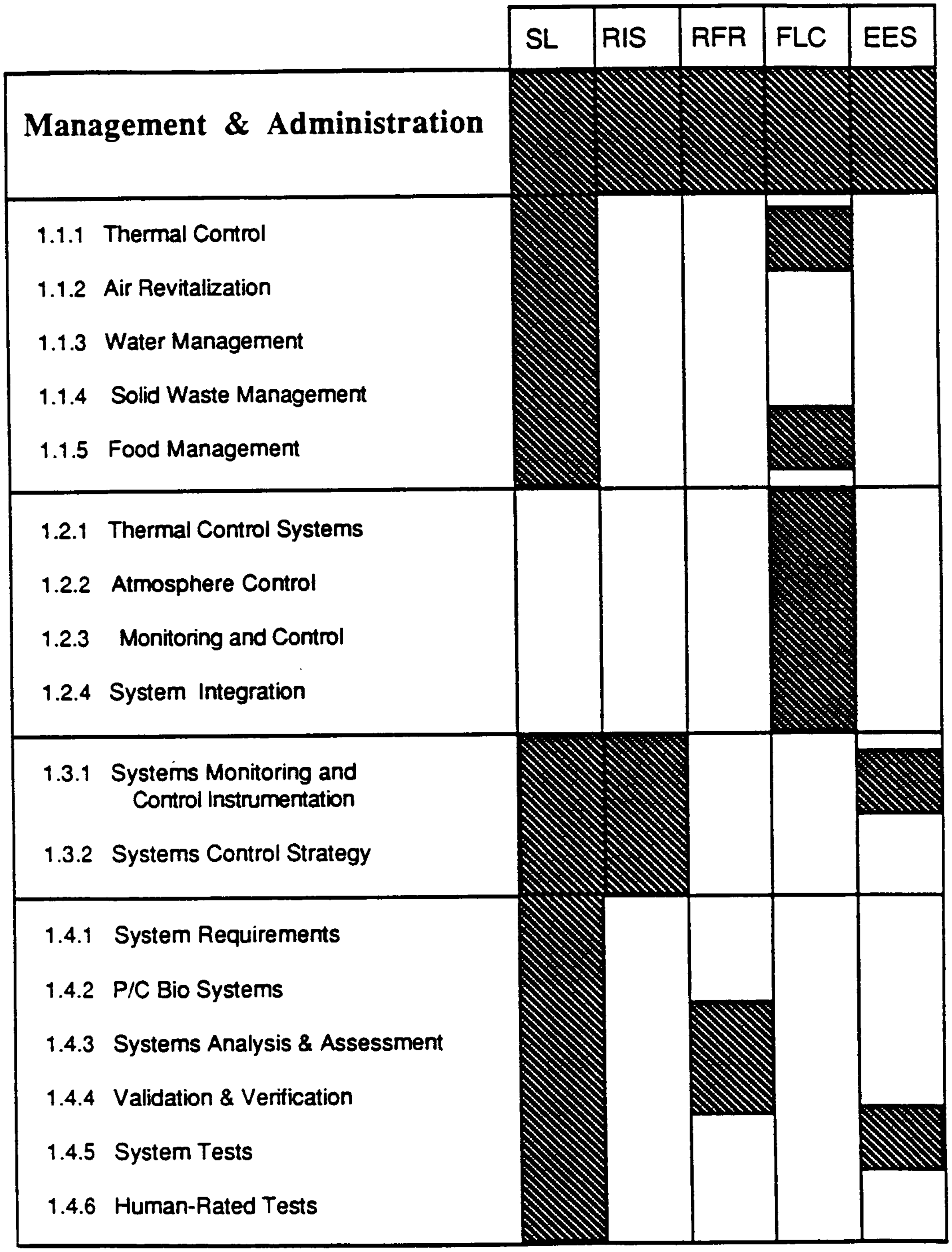

SL
RIS
RFR
FLC
EES
Management & Administration
1.1.1 Thermal Control
1.1.2 Air Revitalization
1.1.3 Water Management
1.1.4 Solid Waste Management
1.1.5 Food Management
1.2.1 Thermal Control Systems
1.2.2 Atmosphere Control
1.2.3 Monitoring and Control
1.2.4 System Integration
1.3.1 Systems Monitoring and Control Instrumentation
1.3.2 Systems Control Strategy
1.4.1 System Requirements
1.4.2 P/C Bio Systems
1.4.3 Systems Analysis & Assessment
1.4.4 Validation & Verification
1.4.5 System Tests
1.4.6 Human-Rated Tests

Figure 2.2.2-2

2.2.2.3 Intercenter Working Group

An Advanced Life Support Intercenter Working Group (IWG) will be established to facilitate both technical and programmatic coordination, cooperation, and communication among the participating centers. The ARC PM will have the responsibility of chairing the IWG sessions which will meet at least twice a year. The IWG sessions will facilitate technology transfer within the specific technical elements of the project, solicit new ideas for technology development, and provide a forum for overall project goals, approaches, and issues. All participating centers will be expected to actively participate in these IWG sessions.

The initial meetings of the IWG in FY89 will consider the following subjects:

- Format and content of subsystem design packages
- Design and structure of a P/C CLLS systems database
- Methodology for archiving validated simulation models

Agreements in the above subject areas early in the project will facilitate communications among the participating centers and contribute to the orderly pursuit of the objectives for each technical element.

2.2.2.4 Networking And Communications

As stated in the Management Approach Section (Section 1.7) of this plan, technical coordination, communications and technology transfer are essential to achieving the goals of the project. Mechanisms for networking and communications among the participating centers must be addressed at an early stage of the work.

The TM at the lead center for each technical element will be responsible for implementing appropriate methods for communicating with the associated support centers. A session of the IWG will be convened in FY90 to discuss plans for a project-wide network for rapid information transfer.

2.2.3 Project Planning

The five-year project plan as described in this document will be reviewed each year. The annual project plan review will allow re-direction of technical focus as mandated by national plans for space exploration, resource availability, or unexpected technological developments. The yearly review of this plan will be conducted by OAST, the ARC Project Manager (PM) and Project Staff, and the participating centers. The ARC PM will have the responsibility for conducting this review, and for modifying, revising, or preparing a new project plan document if necessary.

Each year, the Technical Manager at the lead center for each technical element will solicit task descriptions from the staff at both the lead center and the supporting centers. These task descriptions will include funding requests for both new work and work still in progress. The TM at the lead center will review these task descriptions and make recommendations for funding in the coming fiscal year to the ARC PM. In turn, the PM will present proposed resource allocations, milestones and deliverables to the OAST P/C CLLS Program Manager for approval.

2.2.4 Program Reporting

2.2.4.1 Formal Reports

Formal reports to the OAST Program Manager will be prepared and submitted by the ARC PM on a monthly basis. Status, plans and issues for each technical element will be described in brief narrative fashion. The Technical Manager at the lead center for each technical element will prepare and submit these narratives to the ARC PM for inclusion in the monthly report. Comparisons between actual and scheduled progress and expended and allocated resources will also be included in these reports.

2.2.4.2 Reviews

The Project will be reviewed semi-annually by OAST against schedule, accomplishments, and resources. During these project reviews, each center will contribute in its areas of project activities. There will be at least an annual review of all university grants supported by the project. Reviews will be scheduled and conducted by the ARC Project Manager.

2.3 RESOURCES

The Physical/Chemical Closed-Loop Life Support project is a major undertaking requiring a commitment of significant staffing and funding resources. These commitments are expected to increase during the five years covered by this project plan. The following subsections contain an overview of the resources plan and summaries of both five year and FY89 funding.

2.3.1 Resources Plan

Each of the participating NASA Centers will be expected to commit an appropriate number of civil service staff to those technical elements where the center has an assigned lead or support role (See Subsection 2.2.1.3). Also, it is expected that the participating centers will supplement these civil service staff commitments with assigned support contractor personnel where appropriate. For each technical element in the WBS, the P/C CLLS Technical Manager (TM) at the lead center will confer with the TMs at the supporting centers and reach an agreement on overall staffing for FY89. The TMs at the lead centers will then submit these staffing plans to the ARC PM for review and concurrence. The staffing plans for each technical element will be reviewed and revised on an annual basis beginning in FY90.

The ARC PM will prepare a central Research and Technology Objectives and Plans (RTOP) document for the P/C CLLS project. The TM at the lead center for each technical element will confer with the TMs at the support centers and develop the necessary work element write-ups for inclusion in the RTOP.

Each lead center for a technical element will be responsible for utilizing the assigned funds including allocation to the supporting centers. The TM at the lead center for each technical element will be accountable to the ARC PM for utilization of the assigned funds and will prepare and submit a plan covering the allocation to specific tasks. The ARC PM will be responsible fo reviewing and approving these plans.

2.3.2 Five Year Funding

Table 2.3.2-1 covers the first five years of the P/C CLLS project. Funding has been assigned at the 2-digit WBS level for the period of FY89 through FY93. Estimates of assessments and taxes are included as a separate line item. The bottom-line total for FY89 matches the published guideline. Corresponding totals for FY90 through FY93 are estimates which may well be subject to future revision.

2.3.3 Fiscal Year 1989 Funding

Table 2.3.3-1 summarizes the assignment of FY 89 funds among the participating centers at the 2-digit WBS level. Details of funding for specific tasks are summarized in the central RTOP document for the P/C CLLS project.

For clarity, Portable Life Support Systems (WBS 1.2) have been omitted from Table 2.3.3-1. Funding assignments for this work are addressed in the EVA/Suit Project Plan.

Five Year Funding, $K

	(2-Digit WBS)	FY89	FY90**	FY91**	FY92**	FY93**
1.1	Physical/Chemical Life Support	575	3,400	4,900	6,200	6,500
1.2	Portable Life Support Systems	-Funding is addressed in EVA/Suit Project Plan-				
1.3	Systems Control	200	600	900	1,200	1,300
1.4	System Integration	595*	700	900	1,200	1,600
	Subtotal	1,370	4,700	6,700	8,600	9,400
	Estimated Taxes & Assessments	380	1,300	1,800	2,400	2,600
	Total	**1,750**	**6,000**	**8,500**	**11,000**	**12,000**

* Includes Reserves

** Funding for FY90 - FY93 is subject to further revisions in future

Table 2.3.2-1

Fiscal Year 1989 Funding, $K

		ARC	JPL	JSC	LaRC	MSFC	HQ	TOTAL
1.1	**Physical/Chemical Life Support**	275	0	250	0	50	0	575
1.3	**Systems Control**	0	0	0	0	200	0	200
1.4	**Systems Integration**	150	150	0	0	0	295*	595
	Totals	**425**	**150**	**250**	**0**	**250**	**295**	**1,370**
	Estimated Taxes & Assessments							380
	FY89 Total							**1,750**

* **Includes Reserves**

Table 2.3.3-1

2.4 PHYSICAL/CHEMICAL LIFE SUPPORT

The life support system needed to provide a crew with their daily needs so that they can lead healthy and productive lives in space is composed of several elements. These elements are water management, air revitalization, food management, thermal control, and solid waste management. Supporting elements for systems monitoring and control instrumentation and systems control strategy are also necessary to reduce the risk of system failure, to increase efficiency, and to aid in automation. Automation reduces the amount of time a space inhabitant must spend servicing the life support system and thereby increases productivity.

The water management element of the life support system is responsible for providing the potable and hygiene water needs of a space inhabitant. Air revitalization maintains a habitable atmosphere of the proper gas composition, temperature, humidity and pressure. This element also provides control of airborne contaminants as well as fire detection and suppression. The thermal control element provides acquisition, transport, and rejection of heat to provide a habitable environment. The food management element provides the nutritional and caloric requirements and the solid waste management element is responsible for handling, treatment, and disposal of waste products. In the case of a regenerative or Closed-Loop Life Support system designed for long duration human space missions, the daily needs of a person theoretically can be recovered from output streams from all of these elements.

It is well recognized that habitability sources such as whole body showers, dish washers, laundry washers, etc. have a significant impact on the thermal control, air revitalization, and water management subsystems of a Physical/Chemical life support system. Habitability, however, has not been cited as a separate element in this plan because each of the separate elements of the plan that may be impacted by habitability-related sources are expected to handle the issue. For example, the water management element is expected to process water vapor and liquid streams derived from whole body showers and other hygiene-related activities.

The Closed-Loop Life Support (CLLS) system is much more complex than the systems previously designed for short-duration missions. In a CLLS system, the water management, air revitalization, and food management elements must be concerned with recovering water, oxygen, and possibly generating food from waste materials. Also, the solid waste element must be concerned with minimizing the generation of final residual waste material. In contrast, short-duration missions employ an open-loop system wherein the needs of a person are stored aboard the spacecraft at launch and waste products are stored for return to Earth.

This section of the project plan is concerned with the technology required for CLLS systems, including the Thermal Control, Air Revitalization, Water Management, Solid Waste Management, and Food Management elements. The supporting Systems Monitoring and Control Instrumentation and System Control Strategy elements are covered in Technical Section 2.5 of this plan.

2.4.1 Thermal Control

2.4.1.1 Objectives

The primary objective of the Thermal Control element is to develop the technology necessary to design and construct the Active Thermal Control Systems (ATCSs) to be used on future human space missions to be defined by OEXP. The ATCS for each mission scenario will be expected to perform the following functions:

a) The habitat heat transport subsystem will collect and transport waste heat from heat sources located within the habitable area; these heat sources will include not only heat generated by CLLS components but also heat generated by other sources, such as payloads, experiments, avionics, humans, animals, etc;

b) The habitat heat transport subsystem will transport and transfer the waste heat to the external heat transport subsystem; two heat transport subsystems are used because the habitat heat transport subsystem must use a non-toxic, non-flammable fluid, while the external heat transport subsystem is more concerned with maximizing heat transported per unit mass with less concern for either toxicity or flammability;

c) The external heat transport subsystem will collect and transport waste heat from heat sources located external to the habitable area; these heat sources will include not only the waste heat transferred to the external ATCS from the habitat ATCS, but also heat generated by other sources, such as payloads, experiments, general purpose machinery, other systems, etc.;

d) The external heat transport subsystem will transport and transfer the waste heat to the heat rejection subsystem;

e) The heat rejection subsystem will reject the waste heat to the ambient environment by conduction, convection, radiation, or some appropriate combination of the three;

f) Heat storage devices will be used in the ATCS, when appropriate, in order to reduce the systems-level mass;

Because the ATCS is a key component of any space mission scenario, reliability, safety, and quality assurance are important concerns to be addressed. The ATCS will consequently need to be designed so as to:

- Minimize the potential for failure or damage of components,
- Minimize the need for replacement components,
- Minimize the need for human intervention,
- Maximize ease of repair,
- Include the redundancy, quality, and protection necessary to insure a safe return of the crew members.

An additional objective of the Thermal Control element, therefore, is to determine the requirements to which the ATCS must be designed to insure the safe return of the mission crew. These requirements will be determined by working in conjunction with the System Requirements element (WBS 1.4.1). Further, the Thermal Control element will develop the ATCS components to the specified requirements.

Because the ATCS must be in use continuously and for a long period of time, a system must be developed which is automated as much as possible. Such a system will take advantage of the most recently developed techniques in artificial intelligence to perform the functions of: system monitoring and control; fault detection and analysis; fault correction or repair, when possible; and instruction on the methods of fault correction or repair, when necessary. Consequently, the Thermal Control element will be responsible for the development of instrumentation, sensory equipment, software, and hardware to be used in controlling, monitoring, and maintaining the ATCS.

In order to ensure that the mass is minimized for a particular mission and not just on a system or component level, the ATCS must be optimized on the systems level. This optimization includes not only optimizing mass between the ATCS and other spacecraft systems (e.g., power system) but also between multiple ATCSs operating at different temperature levels (e.g., 2 ^{o}C versus 21 ^{o}C versus 30 ^{o}C).

Since minimizing mass is always a high-priority concern in space flight, every effort should be made to reduce the mass of the system as much as possible. Included in this objective should be the effort to take advantage of the new high-strength, low-mass materials which have become available in recent years. Therefore, the Thermal Control element will take advantage of the advances which have been made in the areas of composite materials, ceramics, polymers, etc.

To reduce development costs, the ATCS designs for the different mission scenarios will use interchangeable hardware whenever possible; but it should be realized that mass optimization on the systems level is considered a higher priority. The use of modular components will be considered, as long as they do not significantly increase the systems level mass over alternate possibilities.

The ability to analyze and predict the performance of the ATCS and its components will be of the utmost importance in the Thermal Control element. Equally as important will be the ability to optimize a system or a component when performing component-, system-, and systems-level trade studies. To develop models that can accurately perform these functions for the ATCS and its components, it will be necessary to develop new methods of predicting pressure drops and heat transfer coefficients, evaporation, condensation, and adiabatic two-phase flow as well as fluid positioning in microgravity and reduced gravity. This effort will consist of developing new predictions, empirical correlations, and Computational Fluid Dynamics (CFD) techniques to allow prediction of these quantities. Therefore, the Thermal Control element is responsible for developing new analytical models and empirical formulae which accurately describe advanced two-phase fluids and fluid flow under reduced gravity conditions, and for developing accurate and efficient CFD techniques for use in ATCS software models.

Within the context of this five-year Project Plan, the objective of the Thermal Control element is to design, develop, and test breadboard versions of the various component alternatives. Further, the software models of the various component alternatives will be developed to such a level that systems-level trade studies can be performed. At the conclusion of the systems-level trade studies, a single ATCS configuration for each mission will be chosen to support the overall integrated P/C CLLS design package milestone.

2.4.1.2 Technical Approach

Thermal control for manned space habitats demands that unique requirements be met in two critical areas. First, the habitat temperature must be controlled within a narrow band to a very specific, relatively low level to maintain the crew's life. An even narrower control band must be maintained to insure the high productivity levels necessary for space flight. This relatively low, narrow temperature control band necessary for human life and the associated physical/chemical life support processes, leads to very difficult heat rejection requirements in the harsh thermal environments associated with lunar or planetary missions.

Second, heat transfer fluids to which the crew can be exposed must meet extremely stringent constraints--they must be absolutely non-flammable and non-toxic. Since toxicity is a strong function of exposure time, the long mission duration associated with future space missions significantly complicates this issue.

In addition to these general requirements, if an artificial gravity environment is required to maintain long-term crew health for interplanetary manned transfer flights, it will present unique thermal control system design constraints. The current two phase/heat pipe concepts developed for Space Station application only operate properly under zero gravity conditions.

Thermal control within the Pathfinder P/C CLLS Program differs from many other aspects of the program in that the thermal system must interact directly with, and be affected by, the ambient environment. Gravity, effective sink temperature, and composition and density of the atmosphere (if any) will all affect the choice and performance of the ATCS for a particular mission. Because of the wide variations in environments, no single ATCS can be singled out which can generically fulfill the requirements dictated by the different mission scenarios under consideration (i.e. lunar base vs. manned Mars mission). Optimization and sizing of the ATCS components will also be affected by the ambient environment and by mission requirements such as power output level, power source, crew size, etc.; consequently, even two ATCSs which use the same components in the same combination can vary substantially in size and performance.

The components which make up an ATCS must be optimized on a systems level in order to assure minimum mass. For example, using a heat pump in the ATCS will certainly reduce the mass and area requirements for the radiators, but it will also increase the size of the power system in the process; a trade study of the combined systems would need to be performed to determine whether the use of a heat pump would be advantageous from a mass optimization standpoint.

The Work Breakdown Structure (WBS) for the Thermal Control element is broken down into six sub-elements:

1.1.1.1 Heat Acquisition
1.1.1.2 Heat Transport
1.1.1.3 Heat Rejection
1.1.1.4 Heat Storage
1.1.1.5 Subsystem and System Analysis
1.1.1.6 Subsystem Test

All of the above sub-elements will contribute to the development and selection of optimized ATCS designs to serve future crewed missions. Of these, Subsystem and System Analysis is the key sub-element that provides guidance for, and receives feedback from the work conducted under the other sub-elements.

Heat Acquisition can be either the acceptance of heat from a heat source (e.g., payloads, avionics, people) or the transfer of heat between two thermal control subsystems. Heat exchangers, cold plates, evaporators, condensers, boilers, etc., all perform the task of heat acquisition for an ATCS.

Development of advanced evaporators and boilers for the ATCS requires a fundamental technology development program. The present level of knowledge allows for the design and optimization of thin film evaporators (where the liquid inventory is controlled by capillary forces). However, serious questions remain about the performance of these devices in microgravity, especially during heat load transients and during recovery from dryout.

There are several types of devices that could be used as heat acquisition devices in the ATCS that are more robust than thin film evaporators. One device in particular is the flow boiler concept. This device has the advantage of higher heat transfer coefficients, and thus smaller volume and weight, over the capillary controlled devices. However, to ensure proper operation and to allow optimization to be performed, more fundamental knowledge must be obtained about their operation in micro-gravity and reduced gravity.

A fundamental technology development program should also be undertaken to develop advanced condensers for the ATCS. The present level of knowledge allows for the design of capillary controlled condensers (that use capillary forces to remove the condensed liquid) and shear controlled condensers (where the incoming vapor momentum is used to remove the condensed liquid).

Improved types of condensers are in various stages of development. One such device uses dropwise condensation to effectively maintain higher heat transfer coefficients than in capillary controlled condensers. Internal surface coatings in the shear controlled condensers would allow dropwise condensation to persist over long periods of time and would therefore substantially increase the heat transfer coefficients, and reduce volume and mass. To allow detailed design and optimization of the dropwise condenser, more fundamental knowledge must be obtained about condensation in a reduced gravity environment.

Heat Transport is the transportation of heat from a heat source to a heat sink. The heat transport between devices in the ATCS will, if possible, be carried out using a two-phase mixture. Two-phase thermal buses have been shown to have approximately 1/15 the mass of comparable single-phase systems. Consequently, two-phase buses have been baselined for the Space Station external to the crew modules. Internal to the modules, however, a single-phase water loop is baselined. The reason for this is that water is the only known thermal working fluid which can be safely used within a habitable environment; and water has a vapor pressure which, at room temperature, is less than the ambient atmospheric pressure, which means that a leak in a two-phase water bus would introduce air into the system which would effectively clog the system. In order to take advantage of the significant savings which two-phase systems offer it will be necessary to locate or develop a new non-toxic fluid with a vapor pressure higher than atmospheric pressure at room temperature. This working fluid could be a single-component working fluid, or it might be azeotropic or binary in nature.

Assuming a non-toxic two-phase fluid cannot be developed, other methods of reducing mass should be considered. One such method would be to suspend Phase Change Material (PCM) particles within a single-phase water coolant loop. This type of system would lessen heat load spikes making it possible to design the system to a narrower, more uniform temperature band.

A mass-saving concept for the external ATCS would be to combine the features of a two-phase thermal bus with a heat pump, resulting in a heat pump which can raise the working fluid temperature as well as transport heat loads over great distances. The mass savings would result in combining the two systems together instead of having two independent components together. This mass savings is based on the assumption that a heat pump/refrigeration system is required or preferred.

Generic technologies which need to be developed are: (1) a non-toxic, two-phase working fluid with a vapor pressure higher than atmospheric pressure at room temperature; (2) a single-phase water loop with PCM particles suspended within the water; and (3) a thermal bus/heat pump subsystem which can increase the working fluid temperature and also transport the waste heat over large distances.

Heat Rejection is the removal of waste heat from the ATCS by radiation, convection, or conduction. The method of heat rejection to be employed is highly dependent upon the environment to be used. In outer space, conduction and convection are not possible, therefore heat rejection by radiation is used. On an airless planet, convection is not possible, so heat rejection is performed by either conduction to the planetary regolith or radiation to space; and the preferred method of heat rejection will depend on other factors such as the effective heat sink temperature or the thermal conductivity of the soil.

The approach to the work to be done for the Thermal Control element assumes that the most likely mission scenarios to be defined by OEXP will be the establishment of a lunar base and/or a manned Mars mission. It is convenient to define technology development requirements in terms of meeting the anticipated demands on the ATCS for these missions.

On the lunar surface, the temperature required by the manned habitat (approx. 23 °C) for environmental control will be below the temperature of the lunar surface (approx. 111 °C) two weeks out of every month. Consequently, heat rejection at the manned habitat temperature during the day cycle will be impossible using Space Station technology--the radiators would absorb more heat than they would reject. The alternatives presently being considered are: (1) to raise the heat rejection temperature of the radiators above the effective sink temperature using a heat pump or refrigeration system; (2) to shield the radiators in such a fashion that they only see the view to space, and not the view to either the sun or the lunar surface; and (3) to combine the two alternatives.

Technologies specific to a lunar base application which need to be developed are: (1) durable, highly efficient heat pumps capable of raising the waste heat temperature from 23 °C to 150-200 °C; (2) heat pipes which operate in the temperature range 150-200 °C; and (3) highly reflective, durable, low-mass devices for shielding thermal radiators from solar and reflected heat loads.

For a Mars Mission, at least two Heat Rejection Subsystems (HRSs) will be needed; one for the Mars Transit Vehicle (MTV), and one for the Mars base.

The HRS for the MTV will radiate heat to the effective 0 °C heat sink of space. It will need to operate at various g-levels for two reasons: (1) due to the extensive in-flight travel time between Mars and the Earth, the MTV will likely be rotated to maintain crew health; (2) the MTV ATCS must be able to perform under conditions of acceleration and deceleration caused by orbital maneuvering. The heat rejection subsystem for the MTV will also need to be deployable and stowable to allow for aerobraking maneuvers, and be optimized to minimize mass on a systems level.

Technologies specific to a MTV application which need to be developed are: (1) methods of deployment and stowage of state-of-the-art radiator systems; (2) development of advanced radiator systems concepts which are low-mass, stowable, gravity-insensitive, and capable of high heat rejection rates.

The Mars base HRS will need to be able to work in a constant 0.38g-field, be optimized to minimize mass, and be resistant to corrosion and degradation caused by the Martian environment. Heat rejection by radiation will be very restricted due to the high concentration of carbon dioxide (CO_2) in the atmosphere. Carbon dioxide tends to absorb radiation in the frequency band at which heat is radiated, thus obscuring the view to space, and causing an insulating (greenhouse) effect in the general vicinity of the radiators. Furthermore, heat rejection by convection to the Martian atmosphere will be extremely difficult because of the thin atmosphere of Mars. Heat rejection by conduction into the Martian regolith is another alternative, although the thermal conductivity of the Martian soil is extremely poor.

Technologies specific to a Martian base application which need to be developed are: (1) a method of soil treatment which will increase the effective thermal conductivity of the Martian soil; (2) an efficient method of transferring the waste heat by convection to the atmosphere; (3) an efficient method of transferring the waste heat by conduction to the Martian regolith; and (4) a method of radiating waste heat despite the greenhouse effect caused by the CO_2 environment.

Heat storage is used to store heat temporarily, and release it again at some later, more opportune moment. Heat storage is used in thermal systems to "smooth out" the varying waste heat and environmental heat loads which are encountered during a mission. By including heat storage devices, the ATCS can be designed for a nominal heat rejection capability instead of designing for the maximum heat rejection capability. Heat Storage can be in the form of a liquid/vapor phase change, a solid/liquid phase change, a crystalline change, an absorption/desorption process, etc. When considered advantageous, heat storage methods will be included in the various ATCSs.

Subsystem and System Analysis is the key sub-element that serves as the mechanism for achieving all of the objectives of the Thermal Control element. Validated dynamic and steady-state computer simulation models will be developed and used to evaluate a wide range of mission-specific designs for the ATCS components and subsystems. Validation of the models will be based on the methodology and procedures developed under the Validation and Verification element (WBS 1.4.4). The validated simulation models of the

ATCS will be utilized in both a stand-alone mode and linked to analogous models that will be developed for the other P/C CLLS subsystems.

Numerous continuing trade-off and performance evaluations will be conducted with the simulation models to develop design packages which describe optimized ATCSs to serve the planned missions. The preparation of each mission-specific design package is included in the Subsystem and System Analysis sub-element. Each design package will contain detailed process flow diagrams for the ATCS, detailed descriptions of studies validating the rationale for selection of an optimized subsystem and supporting documentation. The design package documentation will describe both the interfaces with the other P/C subsystems and an automatic ATCS control and monitoring strategy that is compatible with overall automation of the P/C CLLS system.

The Subsystem and System Analysis sub-element will serve as a focal point for inputs from, and feedback to, other relevant tasks in the program. Inputs for the design evaluations will be supplied from both the other five sub-elements in the Thermal Control element and parallel Subsystem and System Analysis sub-elements contained in the elements for Air Revitalization (WBS 1.1.2), Water Management (WBS 1.1.3), Solid Waste (WBS 1.1.4), and Food (WBS 1.1.5). In turn, the results of the ATCS simulations will provide feedback to guide the various experimental efforts included in the Thermal Control element. Continual information flow to and from the Systems Monitoring and Control Instrumentation (WBS 1.3.1), Systems Control Strategy (WBS 1.3.2) and Systems Analysis and Assessment (WBS 1.4.3) elements will occur during the course of the work.

Subsystem analysis and design evaluation work will begin in FY89 and build up to a sustained effort that continues through FY93. Preparation of preliminary versions of the design packages will begin in FY91. Completion of the final versions will occur in FY93.

The Subsystem Test sub-element will cover supplementary testing that may be required for either validation and verification of the subsystem simulation models or proof-of-concept testing that may arise during the course of the work. It is anticipated that these tests will be conducted on either laboratory-scale versions of the ATCS components or small-scale partially assembled versions of the ATCS designs. The need for specific tests will be defined during efforts performed under the various sub-elements.

All effort for the Subsystem Test sub-element is included under a single omnibus task. Initial model validation and verification-related tests are expected to begin in FY89. Testing will continue through FY93 as required. The design, assembly, and testing of the complete ATCS mission-specific prototypes is not covered by the Subsystem Test sub-element of the Thermal Control element.

2.4.1.3 Description

The following is a summary of the effort to be performed in each sub-element of the WBS for the Thermal Control element. When possible, known concepts are described which should meet the needs of the areas requiring technology enhancement or enabling as described in the Technical Approach sub-topic. This list of sub-elements is not intended to be all-encompassing; to the contrary, it is assumed that concepts will be identified which will better fulfill the mission-specific requirements which have been identified. Those concepts which appear feasible will be considered for inclusion in the Thermal Control element.

HEAT ACQUISITION (WBS 1.1.1.1)

a. Flow Boiler

Flow boiling takes advantage of the gravity gradients on Mars and the moon, and the high heat transfer coefficient associated with boiling.

In FY92, a predictive software model will be developed which is based on the results of the 2-phase fluids research described under the Heat Transport sub-element. Also in FY92, a breadboard test article will be designed and built based on the predictive model. In FY93, the breadboard will be flight tested on the NASA-JSC KC-135.

b. Dropwise Condenser

Dropwise condensation takes advantage of the gravity gradients on Mars and the moon. Drops condense on a cool vertical surface and release waste heat in the process. As condensation continues, the drops grow larger in size and the capillary forces which hold the drop to the surface are eventually overcome by gravity. The drop is pulled downward, where it contacts other drops, and grows even larger. As the drop grows larger, it moves down the surface even faster, colliding with other drops, and removing more and more condensation from the surface until it reaches the bottom. The condensed liquid is then collected and returned to the heat source.

In FY92, a predictive software model will be developed which is based on the results of the 2-phase fluids research described under the Subsystem and System Analysis sub-element. Also in FY92, a breadboard test article will be designed and built based on the predictive model. In FY93, the breadboard will be flight tested on the NASA-JSC KC-135.

HEAT TRANSPORT (WBS 1.1.1.2)

(HABITAT ATCS HEAT TRANSPORT)

a. Non-toxic Heat Transport Fluid for Spacecraft Two-phase Thermal Control System

A fundamental technology program is required to develop a non-toxic two-phase heat transport fluid to take advantage of the inherent capabilities of two-phase flow thermal systems inside manned habitats. The approach should apply basic materials research to "engineer" a new fluid. The desired characteristics which should be inherent in the engineered fluid are high vapor pressure and surface tension, low freezing point, low viscosity, high heat of vaporization, non-corrosiveness, non-flammability, non-toxicity, etc.

In FY90, properties of promising non-toxic two-phase fluids will be verified, and analysis will be performed to evaluate performance of the fluids in a two-phase system as compared to a single-phase water loop. Should no fluids be located that have tolerable characteristics, then an effort to begin development of a non-toxic, two-phase working fluid will begin.

The effort to develop a non-toxic, two-phase fluid will continue until mid-FY92 or until a non-toxic fluid is developed.

b. Single-Phase Water Coolant Loop using Phase Change Material (PCM) Particles Suspended in a Water Working Fluid

This concept uses small spheres of paraffin wax encased in plastic coatings and suspended in the water of a single-phase coolant loop. The wax particles use the heat of fusion to "absorb" the heat while maintaining the coolant loop at an essentially constant temperature. Using a PCM/H2O system will lower the system mass and improve the heat transport characteristics over conventional single-phase water loops.

In FY92, a software model developed from a previous effort will be modified to account for the specific mission and system requirements of the Pathfinder program. Any experiments to verify the modified software model would also be performed in FY92.

c. Habitat ATCS Heat Transport Candidates

In FY92, the candidates for the transportation of heat within the Habitat ATCS will be evaluated with respect to the system and mission requirements which have been identified. Candidate systems will be categorized according to the conditions under which they are most likely to trade advantageously. This information will be used in the Heat Rejection sub-element to evaluate the candidate combinations of the Spacecraft/Planetary Base ATCS.

(EXTERNAL ATCS HEAT TRANSPORT)

d. External ATCS Heat Transport Candidates

In FY92, the candidates for the transportation of heat within the External ATCS will be evaluated with respect to the system and mission requirements which have been identified. Candidate systems will be categorized according to the conditions under which they are most likely to trade advantageously. This information will be used in the Heat Rejection sub-element to evaluate the candidate combinations of the External ATCS.

HEAT REJECTION (WBS 1.1.1.3)

a. Heat Pump Candidates

Under the proper conditions, heat pumps show the capability of saving mass for the radiator subsystem, for the ATCS, and for the planetary base/spacecraft. A large assortment of heat pump concepts presently exist which can be used in a spacecraft/planetary base ATCS, and new heat pump concepts are continually being identified. A heat pump trade study is needed to identify the conditions for which a particular heat pump would be most advantageous.

In FY89, a heat pump trade study will be performed. Candidate concepts will be categorized according to the conditions under which they are most likely to trade advantageously. This information will be used in this sub-element to develop heat pump/heat rejection candidates which appear most promising for the mission and system requirements which have been identified for each mission.

b. Combined Heat Pump/Heat Rejection Component

To properly take advantage of the potential benefit which heat pumps offer, it will be necessary to develop, in conjunction with the heat pump, a heat rejection component which is optimized to perform at the heat pump rejection temperature. This effort would include the performance of trade studies of the heat pump/heat rejection component combination on a systems level to determine the conditions for which a particular heat pump/heat rejection component combination would be practical. At least one heat pump/heat rejection component combination will be developed for each mission scenario.

In FY90, the results of the heat pump evaluation performed in this sub-element will be used to identify heat pump candidates which are applicable to a particular mission. Heat rejection methods and concepts which fulfill the mission and system requirements will be identified and evaluated to determine the feasibility of the approach and compatibility with the respective heat pump. In FY91, conceptual designs and software models will be developed and trade studies of heat pump/heat rejection component combinations will be performed for the different missions. Also in FY91, the top combination for each mission will be chosen and development of the breadboard designs will begin; proof-of-concept experiments will be performed when needed, and predictive analytical models will be developed. In FY92, breadboard components will be fabricated and tested; test data will be used to verify component models.

c. External ATCS Candidates

Different External ATCS concepts can be formed by combining different groups of components in various arrangements. Heat transport components, heat pumps, heat rejection components, and heat storage components can be arranged in different combinations to produce External ATCSs with different characteristics. In order to properly evaluate the different potential External ATCSs, the predictive software models, which have been verified for each component, will be joined in the different combinations in order to predict subsystem level performance for each combination.

In FY93, the External ATCS candidates will be compared with one another according to their ability to fulfill the mission and system requirements. The candidates will be categorized according to the conditions under which they are most likely to trade advantageously.

d. Integrated ATCS Candidates

The different External ATCS candidates which were ranked in the previous task will now be combined with Habitat ATCS candidates to evaluate the best overall ATCS for each mission. The top candidate ATCS's for each mission will be the basis for the prototype hardware development which begins in FY94.

In FY93, ATCS candidates consisting of External ATCS candidates and Habitat candidates will be compared with one another according to their ability to fulfill the system and mission requirements. A single candidate will be chosen for each mission.

(LUNAR BASE HEAT REJECTION)

e. Radiator Shading Concept

The method for heat rejection on the lunar surface which requires the least technological development is the concept of shading the radiators from direct exposure to the sun or from exposure to the lunar surface. For a vertical radiator, radiating off of both sides, four sheets of highly reflective film (e.g. mylar) would be used. Two sheets of the film would start at the base of the radiator, and would extend in opposite directions away form the radiator at some angle with respect to the surface. The remaining two sheets would start at the uppermost end of the vertical radiator, and would also extend in opposite directions away from the radiator at some greater angle with respect to the surface. The end effect, seen from one side, would be of two large V's, one over the other, with a line connecting the bases.

In FY92, a search will be made for highly reflective, durable material for use as a radiator shade. Analysis would be performed to determine the optimal angles and lengths each sheet should have to maximize heat rejection per unit mass. A particular material will be chosen, and a breadboard design and analytical model will be started. Also in FY92, the breadboard design and software model will be completed and the breadboard test article will be fabricated. In FY93, the breadboard will be tested, and the test results will be used to verify the software model.

(MARS TRANSIT VEHICLE (MTV) HEAT REJECTION)

f. Rotating Bubble Membrane Radiator (RBMR) System

The RBMR concept employs a rotating, spherical, radiating surface at the center of which is housed a two-phase nozzle. High quality working fluid is ejected by the nozzle and distributed across the radiating surface. As the fluid condenses on the inner surface, it is moved by centripetal force to the equator of the sphere where it is collected and pumped back through the cycle. The heat, which is released by the condensation process, is conducted through the thickness of the sphere and radiated to space.

The RBMR combines the advantages of two-phase flow, high fin efficiency (approx. 1), and a spherical shape (which maximizes surface area per unit mass) to create a heat rejection system with significantly higher heat rejection capability per unit mass than conventional radiator systems. Additionally, the RBMR is gravity-insensitive due to the rotation of the spherical surface, and is easily stowable due to the pliable nature of the material being considered for use.

In FY90, a KC-135 test article will be built based upon a design funded from another source. The test article will be flown and tested, and results of the test will be used to validate the predictive software model. Design of an RBMR breadboard system will also be completed in FY90, and fabrication will begin. In FY91, fabrication of the breadboard will be completed and tested, and test results will be used to verify the model for predicting RBMR performance.

(MARS BASE HEAT REJECTION)

g. Development and Evaluation of Heat Rejection Systems

Presently no obvious method of heat rejection has been identified which can reject waste heat from the Mars base in a reasonable fashion. This task will identify and evaluate the different concepts for heat rejection from the Mars base. Possible methods to be considered are: a heat pump/heat pipe combination radiator, conduction to the Martian soil after treating the soil to improve thermal conductivity, and convection to the Martian atmosphere through improved liquid-to-gas heat exchangers. Other concepts will also be considered as they become known.

In FY89, candidate methods of heat rejection for the Mars base will be identified, and analysis will be performed to determine feasibility; trade studies, using analytical models, will be performed on concepts considered feasible. Also in FY89, conceptual designs will be developed based on results of trade studies; software modeling and proof-of-concept testing will also be performed to confirm designs. In FY90, development of the breadboard designs will begin; software modification and proof-of-concept testing will continue. In FY91, breadboard test articles will be fabricated and tested. In FY92, breadboard test data will be used to verify software models.

HEAT STORAGE (WBS 1.1.1.4)

a. Heat Storage Component used in Conjunction with a Two-Phase Thermal Bus

By including a heat storage device into the ATCS, it is possible to remove the thermal peaks and valleys which would result from a time-varying heat load. Consequently, the ATCS can be designed for an average heat load rather than a maximum heat load, and a savings in mass should result. It is expected that this task will require little technological development.

In FY91, alternate methods of heat storage will be identified; analysis and trade studies will be performed to rank the different methods according to predefined criteria. Also in FY91, the predictive software model will be developed, the breadboard test article will be designed, and fabrication of the test article will begin. In FY92, fabrication of the breadboard will be completed, and the test article will be tested; test results will be used to verify the software model.

SUBSYSTEM AND SYSTEM ANALYSIS (WBS 1.1.1.5)

a. Utilize Analytical Models to Perform Component-Level, System-Level, and Systems-Level Trade Studies

For each task described in this section, one or several analytical models will be developed for the purpose of performing trade studies on a component, a system, or several systems. These models will consider the effects of fluid type, operating temperature and pressure, heat load, material types, ambient environment, etc., on the mass of the component, system, or systems. Whether the trade study will be performed on the component, the system, or a group of systems will be dependent upon what level that component affects; heat pipes could be optimized on a component level, while heat exchangers would need to be optimized on a system-level. By performing these trade studies, it will be possible to determine the values of each of the parameters traded which will define an optimized system.

b. Develop Component Software Models for use in Predicting Component and System Performance

After the trade studies have been performed, and the parameter values defined, a software model of each component is needed which can accurately predict the performance of that component. This software model will be based on analytical techniques and equations, empirical formulae, known physical characteristics, proof-of-concept tests, etc., and will be used in designing the component. Once the component is designed and tested, the model will be validated to reflect the results of the test.

Once the software models for the various components have been completed, they will be combined to form system models of the various ATCS alternatives. The system models will be used in evaluating and ranking the different ATCS concepts. Once the top ATCSs for each mission have been chosen, the system models will be used in designing the system Ground and Flight Test hardware.

c. Prepare Design Packages

A design package will be prepared to describe the optimized ATCS for each specified mission. Each design package will consist of detailed process flow diagrams, detailed descriptions of studies describing the rationale for selection of the optimized ATCS, and documentation to describe both the automated control and monitoring strategy and the interfaces with other subsystems to be employed in the given mission. Each process flow diagram will contain mass and energy balance summaries that will aid in describing the ATCS efficiency and performance. Also, the process flow diagrams will describe the individual components of the ATCS as well as the interconnections and control/monitoring elements for each technology. Finally, each design package will include the validated models used in preparing the process flow diagrams and accompanying supporting information.

The number of design packages to be prepared as deliverables will depend upon the number of distinct missions defined by the System Requirements element (WBS 1.4.1). The contents and format of these design packages will adhere to the agreements reached by the participating NASA research and development centers (See Section 1.5).

SUBSYSTEM TEST (WBS 1.1.1.6)

All potential ATCS components will be developed to a breadboard level and then tested to demonstrate workability of the technology. Pretest predictions will be performed using the component performance prediction software models developed during the design and fabrication process. The results of the pretest predictions will be compared against actual test data and evaluated. If necessary, modifications to the software models will be made in order to reflect the performance seen during the breadboard testing.

2.4.1.4 Schedule

Figure 2.4.1-1 is an activity schedule for the Thermal Control element that begins with FY89 and extends through FY98. The forgoing descriptions of work under each sub-element of the Work Breakdown Structure cover only the projected activities through the end of FY93. If it is assumed that the mission scenarios to be defined by OEXP will be the establishment of a lunar base and a human Mars mission, the following work projections can be made for FY94 and subsequent years.

In FY94, the specific components will be chosen for each of the three mission-specific ATCSs (i.e. for lunar base, Mars Transit Vehicle, and Mars Base); design efforts for all three systems subsequently will begin. While system-level Ground Test Articles (GTAs) will be sufficient for the lunar base and Mars base ATCSs (due to the presence of a gravity gradient at both locations), a system-level Flight Test Article (FTA) will be designed for the MTV ATCS. Component- and system-level software models will be used in the design of all three systems.

In FY95, fabrication of the three ATCSs will begin.

In FY96, fabrication of the three ATCSs will be completed, and testing of the lunar base and Mars base ATCS GTAs will be performed; system-level models of the two systems will be correlated to reflect data from the system ground tests. Certification of the MTV ATCS FTA will begin.

In FY98, the MTV ATCS FTA will be flight tested on the Shuttle. Data from the flight test will be compared with pretest predictions from the MTV ATCS system model; if necessary, changes to the system model will be made to reflect the results of the flight test.

2.4.1.5 Milestones/Deliverables

Figure 2.4.1-2 lists the major milestones and deliverables for the sub-elements in the Work Breakdown Structure of the Thermal Control element.

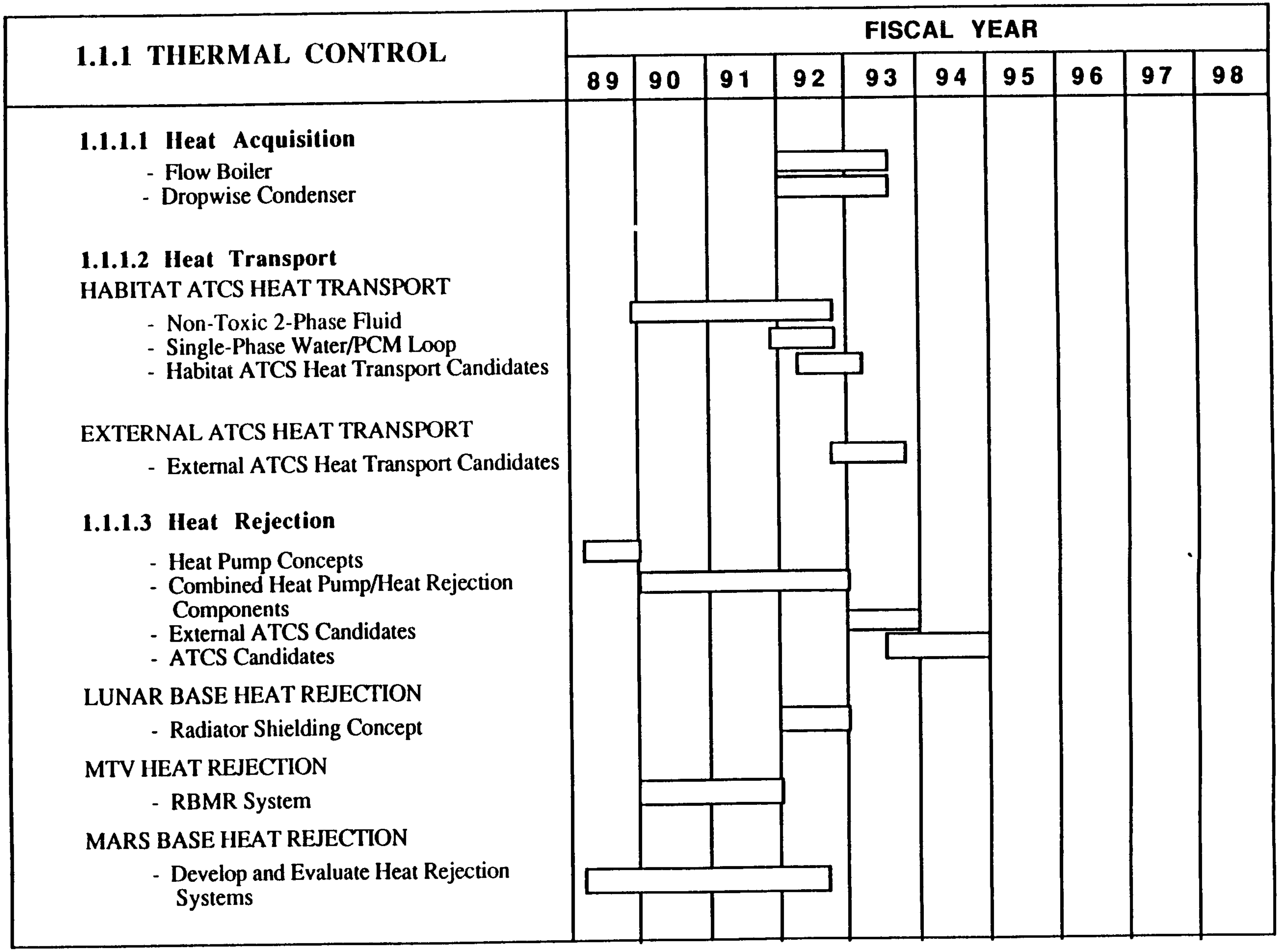

1.1.1 THERMAL CONTROL
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.1.1.1 Heat Acquisition
- Flow Boiler
- Dropwise Condenser
1.1.1.2 Heat Transport
HABITAT ATCS HEAT TRANSPORT
- Non-Toxic 2-Phase Fluid
- Single-Phase Water/PCM Loop
- Habitat ATCS Heat Transport Candidates
EXTERNAL ATCS HEAT TRANSPORT
- External ATCS Heat Transport Candidates
1.1.1.3 Heat Rejection
- Heat Pump Concepts
- Combined Heat Pump/Heat Rejection Components
- External ATCS Candidates
- ATCS Candidates
LUNAR BASE HEAT REJECTION
- Radiator Shielding Concept
MTV HEAT REJECTION
- RBMR System
MARS BASE HEAT REJECTION
- Develop and Evaluate Heat Rejection Systems

Figure 2.4.1-1

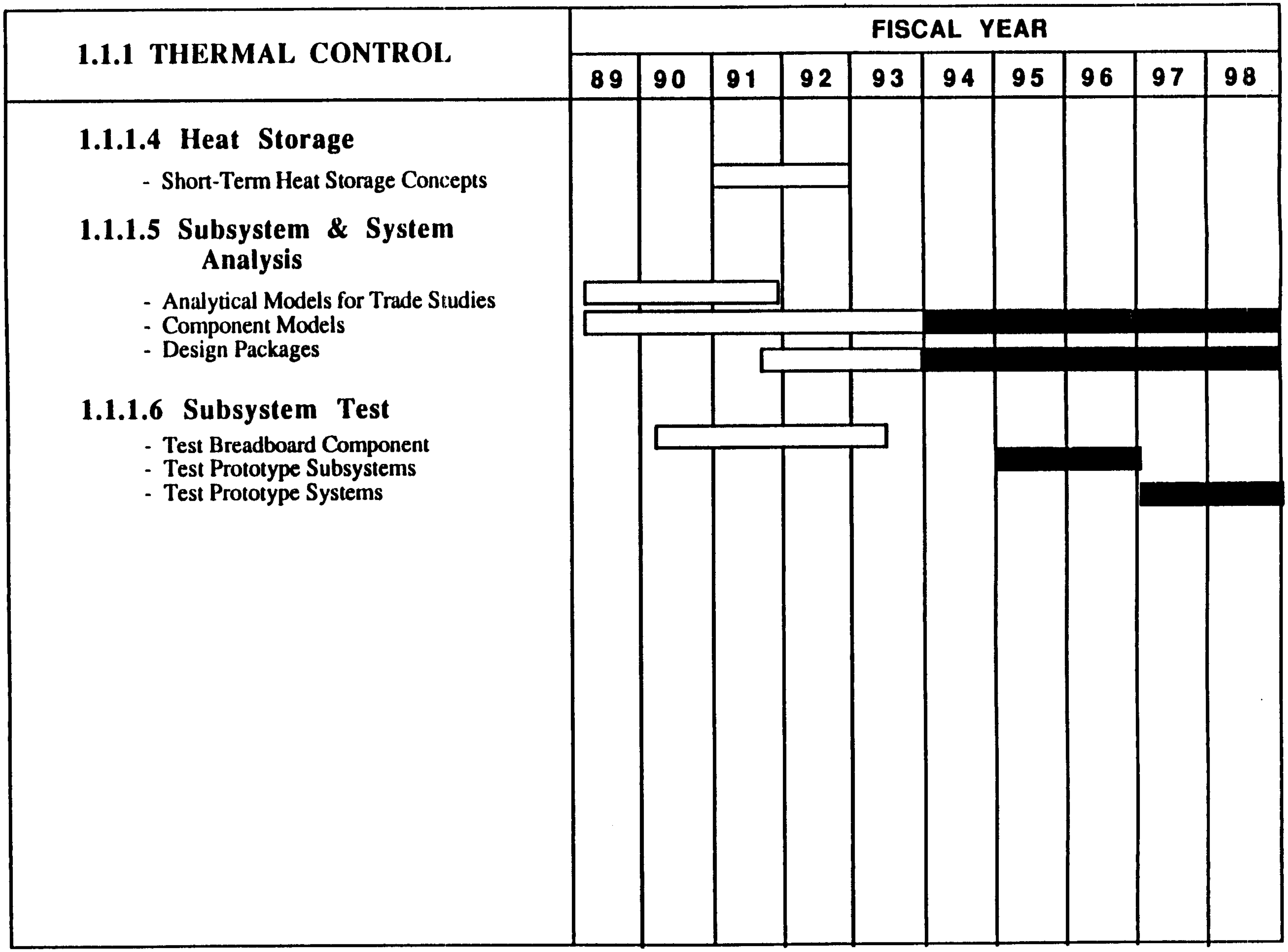


Figure 2.4.1-1 (Cont'd)

Figure 2.4.1-2
Thermal Control
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.1.1.1 HEAT ACQUISITION					
• Flow Boiler					
- Trade Studies Performed				Δ	
- Breadboard Designed				Δ	
- Breadboard Tested					Δ
• Dropwise Condenser					
- Trade Studies Performed				Δ	
- Breadboard Designed				Δ	
- Breadboard Tested					Δ
1.1.1.2 HEAT TRANSPORT					
HABITAT ATCS HEAT TRANSPORT					
• Non-Toxic Transport Fluid					
- Non-toxic Fluid Developed				Δ	
• PCM/H_2O Coolant Loop					
- Software Model Modified				Δ	
• Evaluate Habitat ATCS Heat Transport Candidates				Δ	
EXTERNAL ATCS HEAT TRANSPORT					
• Evaluate External ATCS Heat Transport Candidates					Δ
1.1.1.3 HEAT REJECTION					
• Evaluate Heat Pump Alts.	Δ				
• Heat Pump/Heat Rejection Combination					
- Trade Studies Performed		Δ			
- Breadboards Designed				Δ	
- Breadboards Tested				Δ	
• Evaluate External ATCS Candidates					Δ
LUNAR BASE HEAT REJECTION					
• Radiator Shading Concept					
- Trade Studies Performed				Δ	
- Breadboard Designed				Δ	
- Breadboard Tested				Δ	

(continued on next page)

Figure 2.4.1-2 (cont'd)

Thermal Control
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
MTV HEAT REJECTION					
• RBMR System					
- Breadboard Designed			Δ		
- Breadboard Tested			Δ		
MARS BASE HEAT REJECTION					
• Dev't & Eval. of Heat Rejection Systems					
- Trade Studies Performed		Δ			
- Breadboards Designed				Δ	
- Breadboards Tested				Δ	
1.1.1.4 HEAT STORAGE					
• Single-Phase Loop w/ PCM					
- Trade Studies Performed			Δ		
- Breadboard Designed				Δ	
- Breadboard Tested				Δ	
1.1.1.5 SUBSYSTEM AND SYSTEM ANALYSIS					
• Develop Trade Study Models					
- Models Developed			Δ		
• Develop Component Models					
- Models Developed				Δ	
• Prepare Design Packages					
- Design Packages Complete					Δ
1.1.1.6 SUBSYSTEM TEST					
• Breadboard Components Tested					Δ

2.4.2 Air Revitalization

2.4.2.1 Objectives

The Air Revitalization element covers activities associated with maintaining the composition of air constituents including contaminants and the temperature, humidity, air flow rates, and pressure within specified values for the comfort, health, and safety of the crew.

The primary objectives in this element are to:

a) Assess the status of current technology.

b) Identify all of the functions that are required for automated air reclamation systems.

c) Use high-level mass-balance-based models and other supporting methods of assessment to identify new and potentially useful technologies capable of performing the functions required for missions under consideration.

d) Conduct the laboratory investigations necessary to collect the data required for validation of simulation models.

e) Utilize validated simulation models to evaluate degree of closure, power, mass and volume demands of air revitalization subsystems and to develop optimized subsystems using existing and newly emergent technologies.

f) Use validated simulation models to evaluate the impact of, and required interfaces with, alternative technologies (eg. CELSS) and the use of in-situ resources.

g) Use validated simulation models to prepare optimized designs of air revitalization subsystems for planetary mission scenarios.

Fire detection and suppression activities also fall under the Air Revitalization element. These capabilities will be included in the optimized, mission-specific subsystem designs.

2.4.2.2 Technical Approach

Many factors may influence technology selections for atmospheric revitalization for transit missions and planetary base habitats. Normal operating conditions such as 14.7 psi, 21% O_2, and 78% N_2 may not necessarily be the optimum operating conditions for planetary missions. Physiological requirements may adequately be met by different conditions and new technologies.

The mission duration and resupply period significantly impact technology selections for the air revitalization subsystem. On a Mars mission, with no guarantee of resupply, reduction of consumables and loop closure become critical. Subsystem reliability also takes on a greater significance. In general, the success of any exploration mission will depend upon a highly developed and specialized air revitalization subsystem.

Considering the potential for different operating conditions associated with longer duration space missions, the air revitalization technology shall be designed according to the gas composition of each planetary mission in order to support human metabolic needs. Currently the air revitalization technology has reached a higher maturity level than any other area of technology in life support, however it is not all encompassing especially for particular missions to Mars and Lunar bases due to the nature of the gas compositions associated with these planetary bases. The atmospheric composition of these bases differ considerably, therefore it will be necessary to potentially enhance the current state-of-art in air revitalization technology and pursue new technologies to be adapted to these particular atmospheres.

Several technologies have been developed by NASA for air revitalization beyond the Space Shuttle program. The technology has primarily been concentrated in the areas of carbon dioxide (CO_2) concentration and reduction, O_2 generation, and atmosphere quality monitoring. In addition to these functions, trace contaminant control and humidity control have also been researched. For CO_2 concentration, the main technologies have been the electrochemical CO_2 concentrator (EDC), the solid amine water desorbed (SAWD) process, and the 4-bed molecular sieve. The Sabatier process, the Bosch process, and the carbon formation reactor (CFR) are the principle methods used for CO_2 reduction. Several electrolysis systems have been developed for O_2 generation including a static feed electrolyzer (SFE), a solid polymer electrolyzer (SPE), and a water vapor electrolysis (WVE) process. Trace contaminant control is currently being accomplished by several methods including catalytic oxidation, charcoal adsorption, and chemical absorption. In addition to the trace contaminant technologies, many trace gasses can be removed in a molecular sieve or solid amine unit along with the CO_2. As well as these technologies, cost-effective air revitalization technologies shall still be developed for advanced mission applications in such areas as temperature and pressure control, gas composition, and hydrogen (H_2) and nitrogen (N_2) supply.

Integration aspects of these and other potential new technologies will also be pursued. An evaluation has been made of integrating some of these existing technologies into an independent air revitalization system (IARS) which simultaneously provided CO_2 removal, O_2 generation, and humidity control. The IARS combined the EDC technology with the WVE technology. This type of technology pursuit provides an integrated approach toward regenerable technology which will be critical for longer-duration space flights.

The approach of achieving the objectives of the Air Revitalization will be based on a Work Breakdown Structure that consists of the following nine sub-elements:

1.1.2.1 Temperature and Humidity Control
1.1.2.2 Gas Composition and Pressure Control
1.1.2.3 Trace Contaminant Control
1.1.2.4 CO_2 Removal and Reduction
1.1.2.5 O_2, N_2, H_2 Supply
1.1.2.6 In-situ Resources
1.1.2.7 Subsystem and System Analysis
1.1.2.8 Subsystem Test
1.1.2.9 Plant Interface

All of the above sub-elements will contribute to the advancement of the current technology and the initiation of the development toward the optimization of the air revitalization system design for future manned missions. Of these sub-elements, Subsystem and System Analysis is the key sub-element that provides guidance for, and receives feedback from the work conducted under the other sub-elements. Also, automation and control of the air revitalization processes is a key function that must be performed within the development of each individual mission-specific subsystem. This function will be addressed by working in conjunction with the Systems Monitoring and Control Instrumentation (WBS 1.3.1) and Systems Control Strategy (WBS 1.3.2) elements.

The Temperature and Humidity Control sub-element includes the research and development efforts that are directed toward satisfying the requirements for heating, cooling, humidification (or dehumidification), and ventilation for human needs. The technology pursued will depend on the specific requirements and a thorough knowledge of human thermal ranges for both survival and comfort.

The Gas Composition and Pressure Control sub-element is a mission-specific task. The gaseous composition and the atmospheric pressure will be dependent upon the specific mission and the application. Therefore, once the particular parameters are identified and set for a particular application, then it will be necessary to provide or develop the technologies to satisfy the air revitalization requirements. Flexibility will be provided to adapt a particular mission environment to the desired mission application.

The Trace Contaminant Control sub-element will be necessary due to the quantity and variety of potential contaminants that may exist for longer mission durations. Continuous control must be performed for trace gaseous impurities and particulates. Also, handling of fluids (e.g. methanol, ethanol, heat transport fluids) that are generated or released from the P/C subsystems must be considered. The increased crew exposure time associated with long-duration missions will dictate a reduction in the allowable contaminant concentration levels. This reduction will necessitate the development of a technology base for controlling contaminants for long-duration space missions. Trace contaminant control technologies will stress regenerable techniques for selective removal in order to reduce power, improve reliability and reduce expendables.

The CO_2 Removal and Reduction sub-element is a central task in the air revitalization arena for advanced missions. This task will provide enhancements in reaction phenomenon of existing technologies as well as investigating new methods of CO_2 removal and reduction. New regenerable techniques will be investigated. Provisions will be made to investigate the interface that these technologies may have with other air revitalization technologies including the regeneration of O_2 directly from metabolically produced or concentrated CO_2, thus replacing two processes with one. Collection techniques will be investigated and special consideration will be given to the reduction of consumables, power, and weight. Other concerns exist with extending the life of each technology investigated. These include suiting the technology to the number of crew assigned to the particular advanced mission and meeting low CO_2 partial pressure operation requirements which potentially impacts the equivalent weight of the technology.

The sub-element for O_2, N_2, and H_2 Supply consists of investigating new techniques for increased storage capacity, supply, regeneration, and control of these elements. New and enhanced electrolysis techniques will be investigated to more efficiently generate O_2 and H_2 from water vapor. Innovative technologies will be investigated to extract useful gases directly from the Martian and Lunar atmospheres which could greatly reduce the logistics requirements for long-duration missions. Feasibility studies will be initiated in order to identify any potential alternate technologies or any new technologies that could be integrated together that would warrant further investigation and development.

The In-Situ Resources sub-element will consider mission-specific options for air revitalization within the Lunar and Martian atmospheres. Workshops will be held to identify the in-situ resources available and the data collection/assembly necessary to characterize the nature of the atmospheres in order to generate the air revitalization options to be considered for feasibility studies under the Subsystem and System Analysis sub-element. Concepts generated through these analysis will be investigated further by experimental and paper studies.

Subsystem and System Analysis is a primary sub-element that serves as a foundation for achieving the objectives of the Air Revitalization element. Computer simulation models will be used to evaluate a wide range of mission-specific designs for the air revitalization subsystem for long-duration space missions. Validated simulation models for the air revitalization subsystem will be used in both a stand-alone mode and linked to analogous models for the other P/C CLLS subsystems.

Trade-offs and performance evaluations will be conducted with the simulation models to develop design packages which describe the air revitalization subsystem for future missions. The preparation of each mission-specific design package is included in the Subsystem and

System Analysis sub-element. Each design package will contain detailed process flow diagrams for the optimized subsystem and supporting documentation that describes both the interfaces with other P/C CLLS subsystems and an automatic control and atmospheric monitoring strategy that is compatible with overall automation of the P/C CLLS system. In addition, the Subsystem and System Analysis sub-element will serve as a focal point for inputs from, and feedback to other relevant tasks in the program.

The Subsystem Tests sub-element will be a supplemental testing program for validation and verification of the subsystem simulation models or for the assessment of potential design concepts. The tests will be conducted either on laboratory-scale versions of the individual air revitalization technologies or on small-scale, partially assembled versions of the subsystem designs.

The Plant Interface sub-element will include the experimental work and studies that will lead to an increased understanding of the interface between the air revitalization subsystem and a bioregenerative life support system for food production (CELSS).

2.4.2.3 Description

The following is a summary of the work to be done in each sub-element of the Work Breakdown Structure (WBS) for the air revitalization element.

TEMPERATURE AND HUMIDITY CONTROL (WBS 1.1.2.1)

Requirements will be established that define the comfort temperature and humidity control profiles appropriate for the various habitat mission scenarios. This effort to establish requirements will involve working in conjunction with the System Requirements element (WBS 1.4.1). Technologies will be developed that will satisfy the requirements and readily integrate with the P/C CLLS subsystems. The technology control features, longevity, and reliability will be optimized.

GAS COMPOSITION AND PRESSURE CONTROL (WBS 1.1.2.2)

A program will be established to define the habitat atmospheric requirements to achieve mission scenario goals and the technological areas of research and development that need to be pursued. The requirements include establishing gas composition and pressure regimes, habitat volumes, and airlock/compartment atmosphere recovery needs. This effort to establish requirements will involve working in conjunction with the System Requirements element (WBS 1.4.1). The development of technologies will be pursued that will provide hardware with the high reliability for long term operation to achieve mission goals. Emphasis will be placed on developing those technologies that optimize on the hardware and sensor reliability, longevity, accuracy, control features and the capability for readily integrating with the other P/C CLLS subsystems.

TRACE CONTAMINANT CONTROL (WBS 1.1.2.3)

An experimental program will be pursued in order to reduce expendables associated with activated carbon for contaminant control on extended space missions. Innovative new technologies and improvements on existing techniques will be sought. Emphasis will be placed on regenerating technologies including a supercritical carbon dioxide fluid technique, a vacuum exposure process, and a preparation method Consisting of controlled pyrolysis of carbon molecular sieves. In an effort to reduce power, improve reliability, and expendables, a low temperature catalytic converter will be developed to eliminate atmospheric contaminants not removed by activated carbon.

CO_2 REMOVAL AND REDUCTION (WBS 1.1.2.4)

The removal of carbon dioxide using regenerable technologies is necessary for long duration missions. Several technologies will be examined. The molecular sieve has been shown as a successful sorbent for carbon dioxide removal from the space environment. Research in this area will include two-bed molecular sieve development and a metallic monolith support for the sieve which would provide a more efficient configuration. Photochemical removal of CO_2 will also be investigated as this process could be combined with some oxygen resupply. Another technology to be examined is using electroactive organic-metal complexes for removal and concentration of CO_2. This process could provide a more efficient, reversible process than current regenerative life support systems. Other methods of CO_2 removal which have been investigated in the past will also be considered along with improvements on existing systems.

The reduction of CO_2 into oxygen and useful carbon compounds is also desirable for long term missions, and several alternative technologies will be considered. Photocatalysis is one possible method for CO_2 reduction. For example, photoactivation of CO_2 to produce methanol and water would provide a usable organic compound and ultimately O_2 (via electrolysis of the water). A solid electrolyte process for direct electrolysis of CO_2 to produce O_2 will also be studied. Another chemical process which would supply pure oxygen for life support and eliminate hydrogen used in conventional methods is the catalytic decomposition of CO_2 to O_2 and carbon. Using ultraviolet photolysis to recover oxygen from CO_2 is another possibility.

O_2, N_2, H_2 SUPPLY (WBS 1.1.2.5)

Because cryogenic tankage is unsuitable for long term storage, the applicability of alternate storage methods for O_2, N_2, and H_2 for long duration missions will be investigated. One possibility is using metal hydrides for H_2 storage. An alternate technology consists of using dioxygen complexes of transition metals as a high capacity, regenerable buffer storage system for oxygen. This approach would allow for emergencies and minor upsets in the oxygen level at low energy requirements. Consideration should also be given to ground and flight leak detection and repair in order to conserve gas losses and minimize launch weight associated with leakage replacement.

Electrolysis of water to provide oxygen and hydrogen is a vital step in the development of life support systems. A promising high pressure technology based upon using a solid metal, versus a porous, cathode would avoid the inefficiencies due to product gas recombination associated with current electrolysis technology. Such a system capable of providing various pressure requirements for application to ECLSS, EVA, and propulsion would be a cost efficient approach. Direct electrolysis of water vapor into O_2 and H_2 offers the advantage of avoiding phase change, separation, and handling of liquid water in zero gravity. This technology also lends itself to being "portable" where the module could be used in areas of high metabolic activity without oversizing the central system.

Innovative and revolutionary technologies will be needed to enable production of metabolic gases from available resources to reduce logistics requirements for extended missions. For example, the development of artificial gill technology for extracting O_2 from gas mixtures having low O_2 concentrations may make it possible to extract O_2 from the Martian atmosphere.

Integration of multiple air revitalization technologies could facilitate provision of proper levels of O_2 for crew habitat life support and carbon dioxide for plant growth chambers. Combining technologies associated with water vapor electrolysis, electrochemical carbon dioxide removal, oxygen concentration, and fuel cells into a single subsystem module could be an effective means of closing the life support loop.

IN-SITU RESOURCES (WBS 1.1.2.6)

The ability to recover oxygen from local, in-situ resources must be considered for certain mission scenarios. Examples of such local resources include the Lunar and Martian soils. Annual workshops will be held to review the state of knowledge with respect to each mission-specific resource. Emphasis will will be placed on defining resource availabilities and extraction/production options for further study via Subsystem and System Analysis.

Modeling work conducted under the Subsystem and System Analysis sub-element will identify fundamental database gaps and technology-related questions that must be addressed to allow the inclusion of oxygen/carbon dioxide from in-situ resources in the applicable designs for the air revitalization subsystem. Experimental work and/or paper studies will be pursued to develop database information and answer design-related questions.

SUBSYSTEM AND SYSTEM ANALYSIS (WBS 1.1.2.7)

The first phase of this work will be the use of preliminary computer simulation models of candidate technologies to address air revitalization subsystem design and system integration issues. Input on mission-specific requirements for the air revitalization subsystem will be drawn from the System Requirements element (WBS 1.4.1) and used to formulate a series of preliminary designs. A computer simulation model of each preliminary design will be synthesized by combining the preliminary models of the individual air revitalization technologies. Preliminary design evaluations will be conducted with each of the synthesized simulation models to quantify the impact of known estimates and assumptions. Where applicable, the initial subsystem models will include preliminary definitions of the requirements for interfacing with a bioregenerative life support system.

The computer simulation models for the series of mission-specific designs will evolve continually as work proceeds under both the Air Revitalization element and the other P/C CLLS - related elements. This process of evolution will include increased refinement and sophistication in the models of the air revitalization technologies as estimates and assumptions in the database are replaced by more precise information derived from experimental studies. When necessary, the subsystem simulation models will be revised to incorporate models of new technologies identified through other work under the Air Revitalization element.

During the evolution of each subsystem model, a point or multiple points will be reached where a degree of validation becomes necessary. This process of validation will require some experimental work on a portion of the subsystem to verify that the performance predicted by the model matches that observed in actual operation. The procedure to be followed for validation and verification will be that developed under the Validation and Verification element (WBS 1.4.4). Experimental work required for model validation and verification will be conducted under the Subsystem Tests sub-element of the Air Revitalization element.

Numerous trade-off and performance studies will be conducted with the evolving simulation models of the air revitalization and reclamation subsystem. An initial reduction in the number of alternative designs for a specific mission will be accomplished without complete validation of the associated models. However, only validated computer simulation models will be used for studies that lead to the choice of an optimized design for each mission-specific subsystem. Once the choice of an optimized subsystem design has been made, the associated simulation model will be used for further studies to support the preparation of the corresponding design package.

Continual information flow to and from other elements will be necessary in the course of the work required to arrive at each optimized, mission-specific design for the air revitalization subsystem. Key elements in this process will be the Systems Monitoring and Control Instrumentation element (WBS 1.3.1) and the System Analysis and Assessment element (WBS 1.4.3). Of these, the System Analysis Assessment element will insure that each optimized design has been developed with full consideration of both the interfacing and control strategy requirements.

The second phase of the work for this sub-element will be concerned with preparing one of the primary deliverables from the Air Revitalization element. A design package will be prepared to describe the optimized design of an automated air revitalization subsystem for each specified mission. Each design package will consist of detailed process flow diagrams and documentation to describe both the accompanying control and monitoring strategy and the interfaces with other subsystems to be employed in the given mission. Each process flow diagram will contain mass and energy balance summaries that will aid in addressing the subsystem efficiency and performance. Also, the process flow diagrams will describe the individual components of each air revitalization technology used in the subsystem as well as the interconnections and control/monitoring elements for each technology. The number of design packages to be prepared as deliverables will depend upon the number of distinct mission scenarios defined by the System Requirements element (WBS 1.4.1).

Computer simulation work for this task will consist of those studies with validated models that may be necessary to develop supplementary information for the design packages. Changes in these models that may be necessary for this work will be implemented as required.

SUBSYSTEM TEST (WBS 1.1.2.8)

Work under this element will consist of both the experiments required for verification and validation of the simulation models and the studies of second-generation air revitalization technologies that are found to hold promise through initial investigations of new ideas and concepts. These experiments and studies will be conducted on either laboratory-scale versions of the reclaiming technologies or small-scale, partial systems.

The scope of each set of experiments for model validation and verification will be determined during the work for the Subsystem and System Analysis sub-element. It is expected that these requirements will depend on only those portions of the subsystem that will confirm the predictions of each simulation model and are not intended to substitute for more complete testing of mission-specific prototypes.

Experimental work on new ideas and concepts developed under the various Air Revitalization sub-elements will lead to definitions of technologies that can be considered as "second-generation" options. The understanding of these technologies will not be sufficiently advanced to allow them to be included in the resulting mission oriented, optimized subsystem designs. Nevertheless, these second generation technologies will show sufficient promise to warrant further laboratory-scale investigations with the intent of including them or substituting them at some future time. The necessary further studies will be funded by this element.

PLANT INTERFACE (WBS 1.1.2.9)

Integration of the air revitalization subsystem with a bioregenerative life support system for food production (CELSS) will involve products associated with plant respiration. Experiments will be conducted to characterize these products in terms of atmospheric gas composition that will impact technical decisions on integration methodology. The need for, and scope of these experiments will be defined during the course of both the on-going work of the CELSS Program and the Subsystem and System Analysis effort.

Concepts and ideas on the design of the interface between the air revitalization subsystem and a bioregenerative life support system will be developed during the work for the CELSS Program, the Subsystem and System Analysis sub-element, and the P/C Bio Systems element. Both experimental work and paper studies will be performed to investigate the more promising concepts and provide the necessary information for their possible inclusion in optimized subsystem designs.

2.4.2.4 Schedule

Figure 2.4.2-1 is an activity schedule for the Air Revitalization element that begins with FY89 and extends through FY98. The foregoing descriptions of work under each sub-element of the Work Breakdown Structure cover the projected activities through the end of FY93. However, it will be necessary to extend certain elements beyond FY93. In the case of the Subsystem Tests sub-element, there will be a transition to testing of mission-specific prototypes and evaluation of subsystem performance in both Research Test Facilities and Ground Test Beds. The solid lines in Figure 2.4.2-1 show both the expected extensions of existing activities and the new transition activities that will start after FY93.

2.4.2.5 Milestone/Deliverables

Figure 2.4.2-2 lists the major milestones and deliverables for the sub-elements in the Work Breakdown Structure of the Air Revitalization element. Some of the specific tasks within the sub-elements of the Air Revitalization Work Breakdown Structure do not lend themselves to easily defined milestones. Milestones and deliverables in the sub-elements of In-situ Resources, Subsystem and System Analysis, Subsystem Test, and Plant Interface will extend beyond FY93 and through FY98.

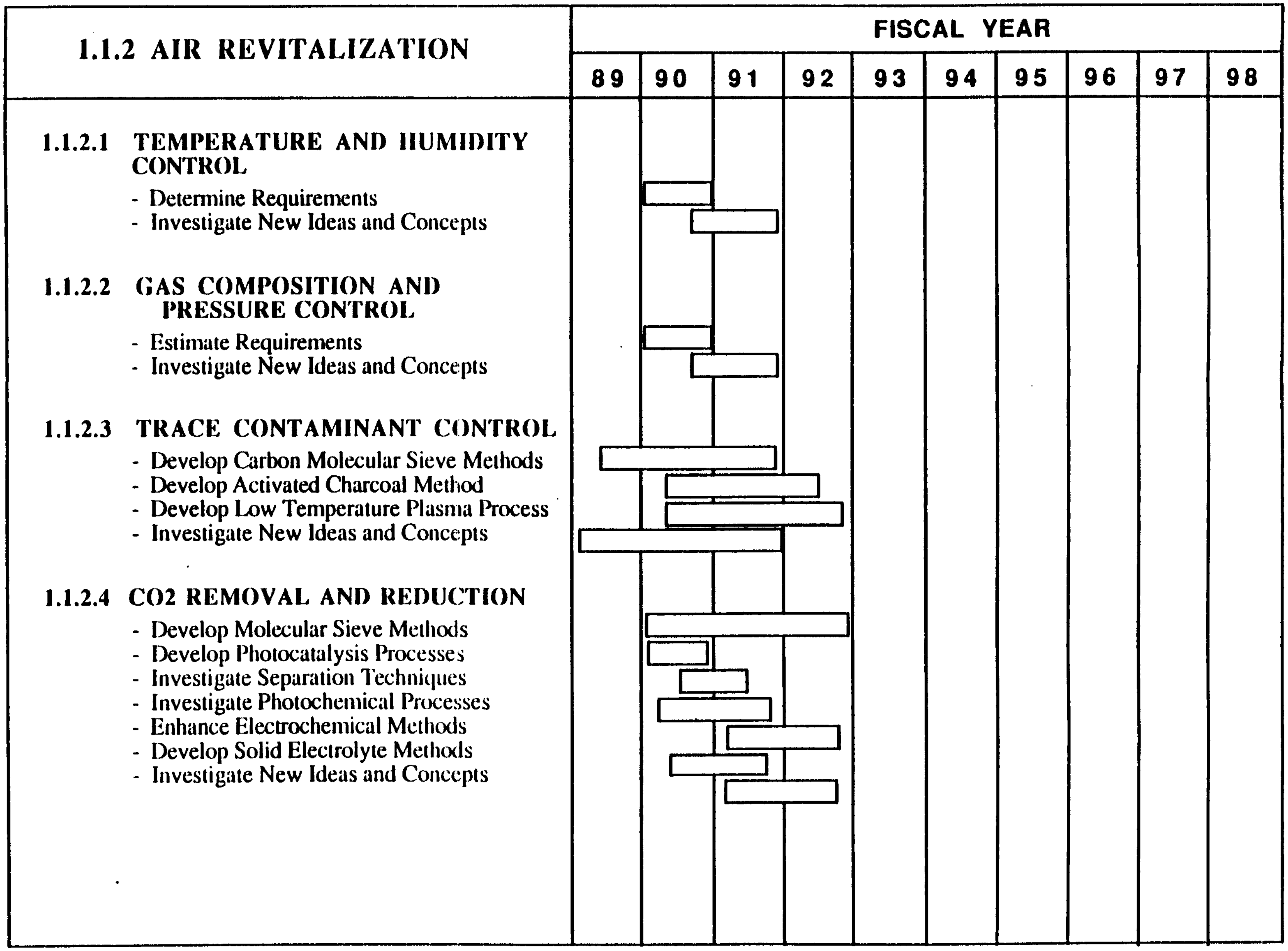

1.1.2 AIR REVITALIZATION
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.1.2.1 TEMPERATURE AND HUMIDITY CONTROL
- Determine Requirements
- Investigate New Ideas and Concepts
1.1.2.2 GAS COMPOSITION AND PRESSURE CONTROL
- Estimate Requirements
- Investigate New Ideas and Concepts
1.1.2.3 TRACE CONTAMINANT CONTROL
- Develop Carbon Molecular Sieve Methods
- Develop Activated Charcoal Method
- Develop Low Temperature Plasma Process
- Investigate New Ideas and Concepts
1.1.2.4 CO2 REMOVAL AND REDUCTION
- Develop Molecular Sieve Methods
- Develop Photocatalysis Processes
- Investigate Separation Techniques
- Investigate Photochemical Processes
- Enhance Electrochemical Methods
- Develop Solid Electrolyte Methods
- Investigate New Ideas and Concepts

Figure 2.4.2-1

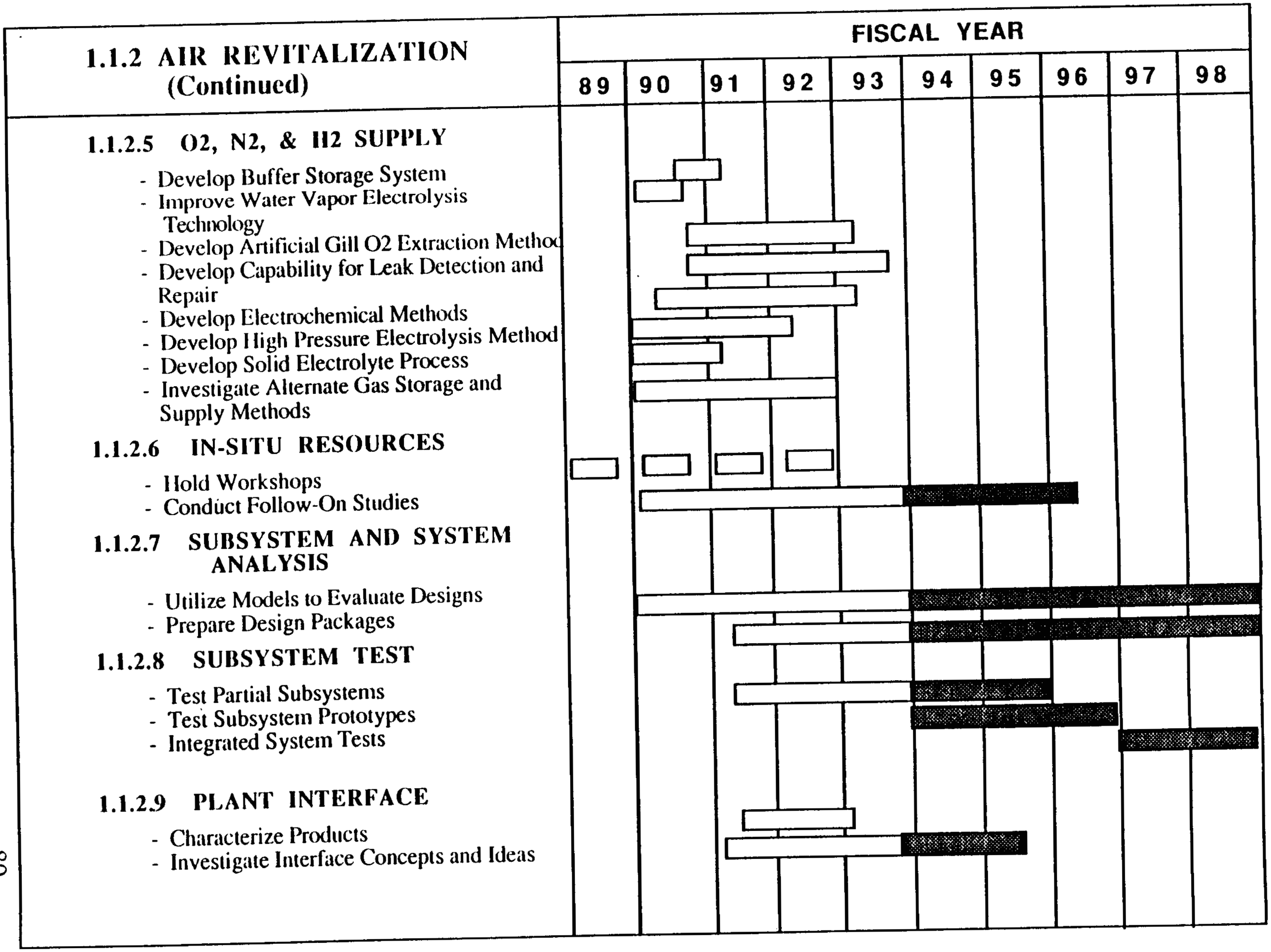


Figure 2.4.2-1 (cont.)

Figure 2.4.2-2
Air Revitalization
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.1.2.1 TEMP AND HUMIDITY CONTROL					
• Determine requirements		Δ			
• Investigate new ideas and concepts			Δ		
1.1.2.2 GAS COMP. AND PRESS. CONTROL					
• Determine requirements		Δ			
• Investigate new ideas and concepts			Δ		
1.1.2.3 TRACE CONTAMINANT CONTROL					
• Develop carbon molecular sieve methods					
- identify promising oxides		Δ			
- demonstrate contaminant removal			Δ		
• Develop activated charcoal method					
- demonstrate extent of regeneration			Δ		
- breadboard assembled				Δ	
• Develop low temp plasma process					
- selection of test configuration		Δ			
- equipment built			Δ		
- report results				Δ	
• Investigate new ideas and concepts			Δ		
1.1.2.4 CO2 REMOVAL AND REDUCTION					
• Develop molecular sieve methods					
- identification of materials and methods		Δ			
- characterization of materials			Δ		
- testing of experimental unit				Δ	
• Develop photocatalysis process					
- synthesize CO2 / transition metal complex on support		Δ			
• Investigate separation techniques					
- lab scale experimental system			Δ		
- preliminary data			Δ		
• Investigate photochemical process					
- feasibility evaluation and conceptual design		Δ			
- testing system complete			Δ		
• Enhance electrochemical methods					
- complete fundamental studies		Δ			
- complete breadboard module				Δ	

(continued on next page)

Figure 2.4.2-2 (Cont.)

Air Revitalization

Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
• Develop solid electrolyte methods					
- complete breadboard fabrication/tests			Δ		
• Investigate new ideas and concepts			Δ		
1.1.2.5 O2, N2, H2 SUPPLY					
• Develop buffer storage system					
- synthesize dioxygen complex and demonstrate regeneration			Δ		
•Improve water vapor electrolysis					
- complete WVE test program		Δ			
•Develop artificial gill O2 extraction					
- complete feasibility study		Δ			
- complete final testing				Δ	
-final report					Δ
• Develop capability for leak detection and repair					
- alternative methods identified			Δ		
- complete testing				Δ	
- final report					Δ
• Develop electrochemical methods					
- perform feasibility investigation			Δ		
- complete preliminary design				Δ	
- demonstrate breadboard					Δ
• Develop high pressure electrolysis					
- develop analytical model		Δ			
- fabricate breadboard			Δ		
-complete breadboard evaluation				Δ	
• Develop solid electrolyte process					
- breadboard performance tests complete			Δ		
• Investigate alternate gas storage and supply methods					
- alternate technologies identified		Δ			
- test development hardware			Δ		
- final report				Δ	

(continued on next page)

Figure 2.4.2-2 (Cont.)

Air Revitalization
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.1.2.6 IN-SITU RESOURCES					
• Workshops (annual)	Δ	Δ	Δ	Δ	
1.1.2.7 SUBSYSTEM AND SYSTEM ANALYSIS					
- System level integration analysis			Δ		
- Analytical support to resolve interface issues				Δ	
- Design packages complete					Δ
1.1.2.8 SUBSYSTEM TEST					
• Preliminary tests					
- validation experiments defined			Δ		
- validation experiments complete				Δ	
1.1.2.9 PLANT INTERFACE					
• Characterize products				Δ	
• Interface concepts and ideas					Δ

2.4.3 Water Management

2.4.3.1 Objectives

The primary objective of the Water Management element is to develop optimized designs of automated water handling and reclamation subsystems for P/C CLLS systems that are intended to serve future human space missions as defined by OEXP. Each optimized subsystem will perform the following water management functions in a continuous, automated mode:

a) Collect and store the various contaminated water streams generated during the course of the mission.

b) Treat the collected water to produce finished streams that meet the applicable quality standards for recycle and re-use.

c) Store and recycle the finished water products as make-ups to the separate, on-board water usage circuits.

d) Collect, store and treat the concentrated, contaminant by-product streams derived from the water treatment processes.

e) Transport the residual contaminants to appropriate interfaces with the solid waste subsystem.

Key deliverables from the Water Management element will be a series of mission-specific design packages containing detailed process flow diagrams and supporting specifications and documentation. The detailed process flow diagrams will describe each optimized design of the automated subsystem. These diagrams will identify both the individual unit processes contained within the complete subsystem and the interconnections between these unit processes that are necessary to supply the required water management functions.

Each water handling and reclamation subsystem must be integrated with other P/C CLLS subsystems and possibly with a bioregenerative life support system for food production.

An additional objective of the Water Management element is the definition of the subsystem interfaces for each design and the development of a thorough understanding of the accompanying interactions. The interfaces with other subsystems will be shown on the detailed process flow diagrams and described in accompanying documentation.

Automated operation of each water handling and reclamation subsystem and continuous monitoring of water quality are requirements for future extended missions. A further objective of the Water Management element is the development of an optimum automatic control and continuous monitoring strategy for each design. Sensor and stream analyzer requirements will be defined and incorporated on the detailed process flow diagrams and accompanying specifications. Feedback will be provided for the Systems Monitoring and Control Instrumentation element (WBS 1.3.1) and Systems Control Strategy element (WBS 1.3.2) to insure that each optimum control strategy is compatible with overall automation of the corresponding P/C CLLS system. This feedback will include definitions of those sensors and analyzers which require further development.

Within the context of this five-year project plan, the final objective of the Water Management element is to initiate the design, construction, and testing of one or more mission-specific subsystem prototypes. Each design package, containing a complete set of detailed process flow diagrams and the supporting documentation of interface and control/monitoring requirements will provide the design basis for each prototype. Subsystem testing and further development at the prototype level will be followed by extensive performance evaluations of integrated P/C CLLS systems in a human-rated, ground-based test bed. The results of these ground-based evaluations will provide the basis for the design and fabrication of flight test hardware for detailed studies in space-based testbeds. The objectives and technical approach for these subsequent tests is described in the System Tests element (WBS 1.4.5) and Human-Rated Tests element (WBS 1.4.6) of this project plan.

2.4.3.2 Technical Approach

Water for drinking, food preparation and hygiene comprises approximately 94 percent by weight of the expendables (water, oxygen and food) that are necessary for humans to lead a healthy and productive life aboard the Space Station. It is assumed that water will continue to represent the greatest percentage of the required expendables for other extended, manned space missions. Therefore, the need to minimize logistic costs of extended missions mandates that emphasis be placed on the design and development of subsystems for near-complete water reclamation and recycling.

A CLLS water handling and reclamation subsystem must collect and treat effluent streams from habitability and hygiene-related sources such as urinals/commodes, showers/hand washes and dishwashing/laundry facilities. Additional water streams will be produced by technologies employed in the air revitalization, solid waste and humidity/temperature control subsystems as well as by in-flight experiments. Inclusion of a bioregenerative plant production system for food supply will result in the generation of collected streams of transpiration water and spent nutrient solution. Finally, the subsystem must be able to treat and recycle water extracted from local resources such as the soil on the planet Mars.

NASA has developed several technologies for reclaiming water from different effluent streams. For example, vapor compression distillation (VCD), thermoelectric integrated membrane evaporation (TIMES) and vapor phase catalytic ammonia removal (VPCAR) processes have all been developed for reclaiming water from streams containing high concentrations of urine. Reverse osmosis (RO) and multifiltration (MF) processes have been developed to reclaim water from more dilute streams such as shower water. Processes such as wet oxidation (WETOX) and supercritical water oxidation (SCWO) may be capable of reclaiming water from both concentrated and dilute effluent streams. On the other hand, cost-effective technologies must still be developed for final treatment operations such as microbial control and removal of trace organics.

A water handling and reclamation subsystem must employ multiple water treatment and reclamation technologies. For example, VCD and RO could be combined with microbial control and trace organic removal technologies to provide a workable subsystem. However, the optimum choice of technologies for a given mission will depend upon numerous factors, e.g., water quality requirements, power availability, requirements for interfacing with other subsystems, available resources at the site of a space habitat, and so forth. Therefore, the development of optimized designs for water handling and reclamation subsystems requires rigorous quantitative analyses of the individual reclamation technologies, their combination to form alternative subsystems and the integration of these alternative subsystems with all other on-board subsystems.

A water handling and reclamation subsystem is actually a small chemical processing plant, operating in space. State-of-the-art computer simulation programs are available for modeling P/C processes of the type used for water reclamation. These simulation programs are employed by the chemical and oil refining industries for a wide range of design and optimization studies. Simulation models of water handling and reclamation subsystem designs can be developed with these same programs and used to perform the required rigorous analyses for preparation of optimized designs.

The approach to achieving the objectives of the Water Management element will be based on a Work Breakdown Structure that consists of the following five sub-elements:

1.1.3.1 Water Processing Technology
1.1.3.2 Plant Interfaces
1.1.3.3 In-Situ Resources
1.1.3.4 Subsystem and System Analysis
1.1.3.5 Subsystem Test

All of the above sub-elements will contribute to the development and selection of optimized water handling and reclamation subsystem designs to serve future human missions. Of these, Subsystem and Systems Analysis is the key sub-element that provides guidance for, and receives feedback from the work conducted under the other sub-elements.

The Water Processing Technology sub-element includes research and development efforts that are directed toward both improving current candidate technologies for water reclamation and gathering basic data for other required technologies which are still in the conceptual stage. Provision is made for funding experimental work on new ideas and concepts for water reclamation and to fill gaps in the supporting database for the current water reclamation technologies. Also, technical assessments of both the current candidate technologies and industrial water reclamation processes will be conducted as part of the work for this sub-element.

The technical assessments and experimental work on existing and required technologies will receive primary emphasis in FY89 through FY91. Experimental investigations of new ideas and the acquisition of experimental data to fill database gaps will be emphasized in FY91 through FY93.

The Plant Interface sub-element includes experimental work and studies that will lead to an increased understanding of the interface between the water handling and reclamation subsystem and a bioregenerative life support system for food production (CELSS). Funding of the bulk of the work for the CELSS Program is provided under the OSSA Base R&T Program. However, subsystem integration-related issues may be identified by Subsystem and System Analysis or other work conducted within the Water Management element.

The Plant Interface sub-element contains two omnibus tasks that are intended to cover interface-related questions which would not otherwise be addressed in the planned work for the CELSS Program. One of these tasks will be used to fund experimental analyses and characterizations of the effluent streams from the bioregenerative life support system to the degree necessary for their incorporation in optimized water handling and reclamation subsystem designs. The other task will fund investigations of concepts and ideas concerning the design of the interface itself. It is anticipated that most of the characterization work will be accomplished in FY90 through FY92. The majority of the work on interface design concepts will occur in FY91 through FY93.

The In-Situ Resources sub-element will consider mission-specific options for treating and recycling water obtained from local resources such as the lunar and Martian soils. Workshops will be held to identify the local resources, assemble data and/or estimates of the water characteristics and formulate reclamation options for feasibility studies by Subsystem and System Analysis. Feedback from these analysis will lead to the formulation of water extraction and reclamation concepts to be investigated by follow-on experimental and paper studies. An omnibus task is included in the In-Situ Resources Sub-element to fund these studies. The workshops will be conducted in FY89 through FY92. The follow-on studies are expected to begin in FY90 and continue through FY93.

Subsystem and System Analysis is the key sub-element that serves as the mechanism for achieving all of the objectives of the Water Management element. Validated dynamic and steady-state computer simulation models will be employed and used to evaluate a wide range of mission-specific designs for the water handling and reclamation subsystem. Validation of the models will be based on the methodology and procedures developed under the Validation and Verification element (WBS 1.4.4). The validated simulation models of the water handling and reclamation subsystem will be utilized in both a stand-alone mode and linked to analogous models that will be developed for the other P/C CLLS subsystems.

Numerous continuing trade-off and performance evaluations will be conducted with the simulation models to develop design packages which describe optimized water handling and reclamation subsystems to serve the planned missions. The preparation of each mission-specific design package is included in the Subsystem and System Analysis sub-element. Each design package will contain detailed process flow diagrams for the optimized subsystem and supporting documentation that describes both the interfaces with the other P/C subsystems and an automatic control and water quality monitoring strategy that is compatible with overall automation of the CLLS system.

The Subsystem and System Analysis sub-element will serve as a focal point for inputs from, and feedback to other relevant tasks in the program. Inputs for the design evaluations will be supplied from both the other four sub-elements in the Water Management element and parallel Subsystem and System Analysis sub-elements contained in the elements that deal with Thermal Control (WBS 1.1.1), Air Revitalization (WBS 1.1.2), Solid Waste (WBS 1.1.4), and Food (WBS 1.1.5). In turn, the results of the water handling and reclamation subsystem simulations will provide feedback to guide the various experimental efforts included in the Water Management element. Continual information flow to and from the Systems Monitoring and Control Instrumentation (WBS 1.3.1), Systems Control Strategy (WBS 1.3.2) and System Analysis and Assessment (WBS 1.4.3) elements will occur during the course of the work.

Subsystem analysis and design evaluation work will begin in FY89 and build-up to a sustained effort that continues through FY93. Preparation of preliminary versions of the design packages will begin in FY91. Completion of the final versions will occur in FY93.

The Subsystem Test sub-element will cover supplementary testing work that may be required for either validation and verification of the subsystem simulation models or assessment of new design concepts that may arise during the course of the work. It is anticipated that these tests will be conducted on either laboratory-scale versions of the individual water reclamation and treatment technologies or small-scale, partially assembled versions of the subsystem designs. The need for specific tests will be defined during work performed under the Water Processing Technology and Subsystem and System Analysis sub-elements.

All work for the Subsystems Test sub-element is included under a single omnibus task. Initial model validation and verification-related tests are expected to begin in FY90. Testing work will continue through FY93 as required. The design, assembly and testing of complete subsystem mission-specific prototypes is not covered by the Subsystem Test sub-element of the Water Management element.

2.4.3.3 Description

The following is a summary of the work to be done in each sub-element of the Work Breakdown Structure (WBS) for the Water Management element.

WATER PROCESSING TECHNOLOGY (WBS 1.1.3.1)

a. Trace Organic Removal

An experimental program will be pursued to develop a trace organic removal process that can be applied in a water handling and reclamation subsystem. Emphasis will be placed on those technologies which do not require potentially hazardous reagents and which can be readily integrated with the other P/C CLLS subsystems. Development of an effective trace organic removal process will fill a major void in the present slate of water reclamation technologies.

Laboratory testing work will be initiated in FY89 and completed in FY90. Design, fabrication and testing of mission-specific and prototype versions of the technology will follow in succeeding years with completion targeted for FY92.

b. Microbial Control

Research will be conducted on methods for microbial control in a water handling and reclamation subsystem. Mechanisms of microbial attachment will be studied with the intent of developing recommendations for materials of construction that will reduce the tendency for biofilm formation. Studies will be conducted on the mechanisms of microbial resistance to disinfection and potential methods for control of planktonic organisms in the reclaimed water streams. Development of an effective microbial control technology will aid in both safeguarding human life and maintaining the performance of the equipment in the subsystem.

Laboratory studies will commence in FY90. Control technology selection, component procurement, and laboratory-scale testing will occur in succeeding years. Preparation of a final report is slated for FY93.

c. Improved RO Membranes

Development work will be conducted on the production of RO membranes with increased tolerance to high temperatures, improved resistance to chemical/microbial degradation, and fouling. Membranes with the foregoing properties will improve the overall performance of RO in a water handling and reclamation subsystem.

Membrane testing and development work will occur in FY89 and FY90. Extended preprototype testing will be conducted in FY91 with final report preparation in FY92.

d. Technical Assessments and Surveys

Comprehensive technical assessments of current life support-oriented water reclamation technologies will be prepared from a historical perspective. The intent of these assessments will be to review key decisions made during past development efforts and thereby to suggest directions for further work.

An in-depth survey of industrial wastewater recovery processes will be conducted to determine if there are existing technologies that can be adapted to water handling and reclamation systems for manned space missions. The survey will cover technologies practiced in both the United States and abroad. The candidate technologies identified in the survey will be characterized analytically and the potential payoff for usage will be determined.

Both the technical assessments and the survey will be started in FY89. Completion is scheduled for early in FY90. The reports containing analytical characterizations, payoff determinations, and recommendations will be issued in late FY90 and early FY91.

e. Investigations of New Ideas & Concepts

New ideas and concepts for water reclamation can be expected to arise from within NASA, universities, and the industrial sector during the work on the Water Management element. Sources of these new ideas and concepts can include the above-listed experimental tasks, the survey of wastewater recovery processes and work conducted for the Subsystem and System Analysis sub-element. Experimental work and preliminary assessments will be performed to further investigate the more promising ideas with the intent of determining their applicability in a subsystem for water handling and reclamation. As stated in Section 1.5, the intent of this work is to provide the basis for inclusion of promising new ideas and concepts in the design packages to be prepared as project deliverables.

The investigation of new ideas and concepts will begin as early as FY90 and will continue through FY93.

f. Follow-On Experiments

Needed follow-on experiments will be defined during the course of the work on the Water Management element. In particular, gaps in the supporting database for the various water reclamation technologies will be identified during the utilization of the subsystem simulation models. It is expected that these gaps in the database will include a lack of the necessary physical and thermodynamic properties as well as the absence of rate coefficients for key chemical reactions. Also, a better understanding of fundamental process mechanisms may be necessary for improving the simulation models of certain water reclamation technologies. Experimental work is usually required to fill these types of gaps in the database.

Of necessity, work for this omnibus task cannot start until the Subsystem and System Analysis and other lead efforts are well underway. It is expected that some work will be necessary starting in FY90. The requirement for these types of experiments is expected to increase markedly in FY91 through FY93. Some of these follow-on experiments may be continued beyond FY93 to develop further data that will support the assembly of mission-specific prototypes for the optimized water handling and reclamation subsystems.

PLANT INTERFACE (WBS 1.1.3.2)

a. Effluent Characterization

Integration of the water handling and reclamation subsystem with a bio-regenerative life support system for food production (CELSS) will involve effluent streams such as transpiration water and spent nutrient solution. Experiments will be conducted to characterize these streams in terms of those physical and chemical properties that will impact technical decisions on integration methodology. The need for, and scope of these experiments will be defined during the course of both the on-going work of the CELSS Program and the Subsystem and System Analysis sub-element.

This omnibus task is intended to cover subsystem design-related effluent characterization experiments that would otherwise not be conducted as a part of the CELSS Program.

Work is expected to begin at a relatively low level in FY89, expand during FY90-92 and taper off in FY93.

b. Interface Concepts/Ideas

Concepts and ideas on the design of the interface between the water handling and reclamation subsystem and the bioregenerative life support system will be developed during the work for the CELSS Program, the Subsystem and System Analysis effort for the P/C CLLS Water Management element, and the P/C Bio Systems element (WBS 1.4.2). Both experimental work and paper studies will be performed to investigate the more promising concepts and provide the necessary information for their possible inclusion in optimized subsystem designs.

Work for this omnibus task will begin in FY90 and build to a sustained effort in FY91 through FY93. Some of the work may be continued beyond FY93 to provide further data in support of the assembly of mission-specific prototypes for optimized water handling and reclamation subsystem designs.

IN-SITU RESOURCES (WBS 1.1.3.3)

a. Workshops

The ability to treat and recycle water obtained from local, in-situ resources must be considered for certain mission scenarios. Examples of such local resources include the lunar and Martian soils. Annual workshops will be held to review the state of knowledge with respect to each mission-specific resource. Emphasis will be placed on defining resource availabilities, water characteristics and extraction/reclamation options for further study via Subsystem and System Analysis.

These annual workshops will be held in FY89 through FY92.

b. Follow-On Studies

Both the above-described workshops and the Subsystem and Systems Analysis work for the Water Management element will identify fundamental database gaps and technology-related questions that must be addressed to allow the inclusion of water from in-situ resources in the applicable designs for the water handling and reclamation subsystem. Experimental work and/or paper studies will be pursued to develop database information and answer design-related questions.

Follow-on study work is expected to begin in FY90 and continue at increasing levels through FY93. It will be necessary to continue some of this work beyond FY93 to support the assembly of optimized water handling and reclamation subsystem prototypes for those missions that will employ water recovery from in-situ resources.

SUBSYSTEM AND SYSTEM ANALYSIS (WBS 1.1.3.4)

a. Model Development & Design Evaluations

The first phase of this task will be the utilization of a preliminary, computer simulation model for each candidate water reclamation technology that can be identified at the start of the work. Gaps in the supporting database and other related questions will be defined during the initial studies with each model and used to formulate the scope of the follow-on studies to be conducted as a separate task under the Water Processing Technology sub-element. Assumptions, estimates and analogies will be employed to the extent necessary to fill the gaps in the database and thereby enable the performance of subsystem analysis with a preliminary model of each water reclamation technology. Since the individual candidate technologies vary widely in state of development, the corresponding preliminary models will differ in terms of sophistication at this stage of the work.

Input on mission-specific requirements for the water handling and reclamation subsystem will be drawn from the System Requirements element (WBS 1.4.1) and used to formulate a series of preliminary designs. A computer simulation model of each preliminary design will be synthesized by combining the preliminary models of the individual water reclamation technologies. Preliminary design evaluations will be conducted with each of the synthesized simulation models to quantify the impact of known estimates and assumptions. Where applicable, the initial subsystem models will include preliminary definitions of the requirements for interfacing with a bioregenerative life support system and for accepting water derived from in-situ resources.

The computer simulation models for the series of mission-specific designs will evolve continually as work proceeds under both the Water Management element and the other P/C-related elements. This process of evolution will include increased refinement and sophistication in the models of the water reclaiming technologies as estimates and assumptions in the database are replaced by more precise information derived from follow-on experiments. When necessary, the subsystem simulation models will be revised to incorporate models of new reclamation technologies identified through other work under the Water Management element.

During the evolution of each subsystem model, a point or multiple points will be reached where a degree of validation becomes necessary. This process of validation will require some experimental work on a portion of the subsystem to determine if the performance predicted by the model matches that observed in actual operation. The procedure to be followed for validation and verification will be that developed under the Validation and Verification element (WBS 1.4.4). Experimental work required for model validation and verification will be conducted under the Subsystem Tests sub-element of the Water Management element.

Numerous trade-off and performance studies will be conducted with the evolving simulation models of the water handling and reclamation subsystem. An initial reduction in the number of alternative designs for a specific mission will be accomplished without complete validation of the associated models. However, only validated computer simulation models will be used for studies that lead to the choice of an optimized design for each mission-specific subsystem. Once the choice of an optimized subsystem design has been made, the associated simulation model will be used for further studies to support the preparation of the corresponding design package.

Continual information flow to and from other elements will be necessary in the course of the work required to arrive at each optimized, mission-specific design for the water handling and reclamation subsystem. Key elements in this process will be the Systems Monitoring and Control Instrumentation element (WBS 1.3.1), the Systems Control Strategy element (WBS 1.3.2) and the System Analysis Assessment element (WBS 1.4.3). Of these, the Systems Analysis and Assessment element will insure that each optimized design has been developed with full consideration of both the interfacing and control strategy requirements.

Work in FY89 will concentrate on the utilization of simulation models for the reclamation technologies and the accompanying definition of database requirements. The synthesis of subsystem models and the evaluation of the associated designs including model validation will occur in FY90 and FY91. Final design optimization studies and the transition to supporting simulations for preparing the design packages will occur in FY92 and FY93. Further refinement and upgrading of the subsystem design simulation models will occur beyond FY93 in support of the assembly and testing of the mission-specific prototypes.

b. Design Package Preparation

This element will cover the necessary work for preparing the primary deliverable from the Water Management element. A design package will be prepared to describe the optimized design of an automated water handling and reclamation subsystem for each specified mission. Each design package will consist of detailed process flow diagrams and documentation to describe both the accompanying control and monitoring strategy and the interfaces with other subsystems to be employed in the given mission. Each process flow diagram will contain mass and energy balance summaries that will aid in addressing the subsystem efficiency and degree of closure of the water loop (i.e., % recovery). Also, the process flow diagrams will describe the individual components of each water reclamation technology used in the subsystem as well as the interconnections and control/monitoring elements for each technology. Finally, each design package will include the validated subsystem models used in preparing the process flow diagrams and accompanying supporting information.

The number of design packages to be prepared as deliverables will depend upon the number of distinct mission scenarios defined by the System Requirements element

(WBS 1.4.1). The detailed contents and format of these design packages will adhere to the agreements reached by the participating NASA R & D and development centers (See Section 1.5).

Computer simulation work for this task will consist of those studies with validated models that may be necessary to develop supplementary information for the design packages. Changes in these models that may be necessary for this work will be implemented under the above-described Model Development and Design Evaluations task.

Work on the preparation of the design packages will begin in FY91 and build to a peak effort in FY92 and FY93. Follow-on work in the form of design package revision and upgrading will continue after FY93 as work proceeds on the assembly of mission-specific prototypes.

SUBSYSTEM TEST (WBS 1.1.3.5)

a. Preliminary Tests — Partial Subsystems

Work under this element will consist of both the experiments required for verification and validation of the simulation models and the studies of second-generation water reclamation technologies that are found to hold promise through initial investigations of new ideas and concepts. These experiments and studies will be conducted on either laboratory-scale versions of the reclamation technologies or small-scale, partial subsystems.

The scope of each set of experiments for model validation and verification will be determined during the work for the Subsystem and System Analysis sub-element. It is expected that these requirements will depend upon the nature of the individual, mission-specific designs for the water handling and reclamation subsystem. The resulting experiments will focus on only those portions of the subsystem that will confirm the predictions of each simulation model and are not intended to substitute for more complete testing of mission-specific prototypes.

Experimental work on new ideas and concepts under the Water Processing Technology sub-element will lead to definitions of water reclamation technologies that can be considered as "second-generation" options. The understanding of these technologies will not be sufficiently advanced to allow them to be included in the resulting mission oriented, optimized subsystem designs. Nevertheless, these second generation technologies will show sufficient promise to warrant further laboratory-scale investigations with the intent of including them or substituting them at some future time. The necessary further studies will be funded by this element.

Work on the validation and verification tests will be conducted in FY90 and FY91. The further studies on second generation technologies will form the bulk of the work in FY92 and FY93. In some cases, the investigations of the second generation technologies will carry forward beyond FY93.

b. Test Subsystem Prototypes

This work is expected to begin in FY94 and continue through FY96. The objectives and approach will follow that outlined in the System Tests element (WBS 1.4.5).

c. Integrated P/C Test Bed Studies

Tests of this type are expected to begin in FY97 and continue beyond FY98. The work will adhere to the objectives and approaches described in the System Tests (WBS 1.4.5) and Human-Rated Tests (WBS 1.4.6) elements.

2.4.3.4 Schedule

Figure 2.4.3-1 is an activity schedule for the Water Management element that begins with FY89 and extends through FY98. The foregoing descriptions of work under each sub-element of the Work Breakdown Structure cover only the projected activities through the end of FY93. However, it will be necessary to extend certain elements beyond FY93. In the case of the Subsystem Tests sub-element, there will be a transition to testing of mission-specific prototypes and evaluation of subsystems in integrated P/C Test Beds. The solid lines in Figure 2.4.3-1 show both the expected extensions of existing activities and the new transition activities that will start after FY93. A task flowsheet for development of CLLS systems is provided in Technical Section 1.7 of this project plan.

2.4.3.5 Milestones/Deliverables

Figure 2.4.3-2 lists the major milestones and deliverables for the sub-elements in the Work Breakdown Structure of the Water Management element. Of these, the most important milestones are those for the various stages of the work for the Subsystem and System Analysis sub-element. The final design packages prepared under this sub-element constitute the primary deliverables from the Water Management element. Each of these design packages will describe an optimized, automated, mission-specific subsystem for water handling and reclamation.

Some of the specific tasks within the sub-elements of the Water Management Work Breakdown Structure do not lend themselves to easily defined milestones. Investigations of new water reclamation concepts and ideas on new designs for interfacing with a bioregenerative life support system may lead to the definition of additional experiments to be conducted after FY93. However, those studies that are directed toward supplying information for the Subsystem and System Analysis must be completed in a timely fashion to avoid slippage in achieving the objectives of the Water Management element. These efforts include the follow-on experiments to fill gaps in the database and the preliminary tests of partial subsystems that will provide information for model validation.

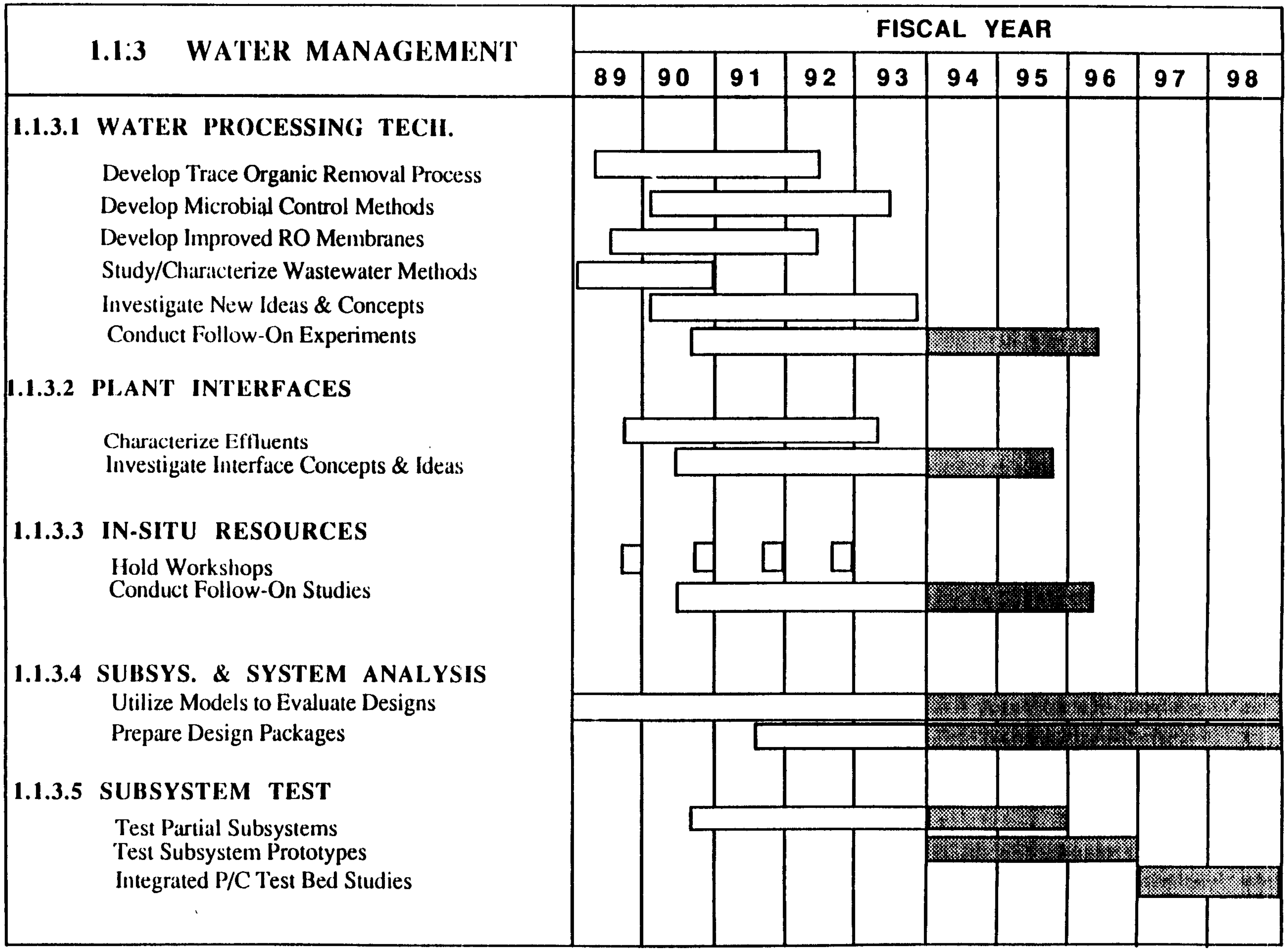

1.1.3 WATER MANAGEMENT
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.1.3.1 WATER PROCESSING TECH.
Develop Trace Organic Removal Process
Develop Microbial Control Methods
Develop Improved RO Membranes
Study/Characterize Wastewater Methods
Investigate New Ideas & Concepts
Conduct Follow-On Experiments
1.1.3.2 PLANT INTERFACES
Characterize Effluents
Investigate Interface Concepts & Ideas
1.1.3.3 IN-SITU RESOURCES
Hold Workshops
Conduct Follow-On Studies
1.1.3.4 SUBSYS. & SYSTEM ANALYSIS
Utilize Models to Evaluate Designs
Prepare Design Packages
1.1.3.5 SUBSYSTEM TEST
Test Partial Subsystems
Test Subsystem Prototypes
Integrated P/C Test Bed Studies

Figure 2.4.3-1

Figure 2.4.3-2
Water Management
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.1.3.1 WATER PROCESSING TECH.					
• Trace Organic Removal					
Lab Testing Complete		Δ			
Breadboard Unit Tested			Δ		
Prototype Tested				Δ	
• Microbial Control					
Mechanism Studies Complete			Δ		
Control Processes Selected				Δ	
Process Tests Complete					Δ
Final Report					Δ
• Improved RO Membranes					
Development/Testing Complete		Δ			
Preprototype Testing Complete			Δ		
Final Report				Δ	
• Technical Assessments & Surveys					
Assessments/Surveys Complete		Δ			
Reports Issued			Δ		
• New Ideas & Concepts					
Feasible Technologies Identified			Δ		
• Follow-On Experiments					
Major Database Gaps Filled				Δ	
1.1.3.2 PLANT INTERFACES					
• Effluent Characterization					
Preliminary Characterizations				Δ	
Final Characterizations					Δ
• Interface Concepts & Ideas					
Interim Interface Definitions				Δ	
1.1.3.3 IN-SITU RESOURCES					
• Workshops (annual)	Δ	Δ	Δ	Δ	
• Follow-on Studies					
Preliminary Reclamation Methods			Δ		
Interim Reclamation Methods				Δ	

(continued on next page)

Figure 2.4.3-2 (Continued)
Water Management
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.1.3.4 SUBSYSTEM & SYSTEM ANALYSIS					
• Model Utilization & Design Evaluation					
Preliminary Technology Models	Δ				
Preliminary Subsystem Designs		Δ			
Preliminary Subsystem Models		Δ			
Validated Subsystem Models				Δ	
Mission Specific Designs Chosen				Δ	
Designs Optimized				Δ	
• Design Package Preparation					
Preliminary Packages Assembled				Δ	
Final Packages Completed					Δ
1.1.3.5 SUBSYSTEM TEST					
• Preliminary Tests - Partial Subsystems					
Validation Experiments Defined		Δ			
Validation Experiments Complete			Δ		

2.4.4 Solid Waste Management

2.4.4.1 Objectives

The primary objective of the Solid Waste Management element is to develop optimized designs of automated solid waste management subsystems for P/C CLLS systems that are intended to serve future crewed space missions as defined by OEXP. A solid waste management subsystem must be capable of handling and processing both solids-intensive and totally solid streams from numerous sources. These sources and the compositions of the streams will vary depending upon both the mission scenario and the overall design of the integrated P/C CLLS system.

The following secondary objectives will have to be met to provide solid waste management subsystems for long-duration space missions:

a. Characterization of all potential input streams including, for example, human waste, trash, waste from laboratory experiments, and residual waste streams from other P/C CLLS subsystems.

b. Identification of processes for the separation, stabilization, treatment, reclamation or storage of these waste streams including destruction, conversion, and/or compaction.

c. Development of candidate subsystem designs by synthesis of process technologies and subsequent evaluation through an appropriate mix of computer modeling, laboratory experiments and testing of breadboard prototype hardware.

d. Development of optimized, mission-specific designs for automated solid waste management subsystems through subsystem and system analysis including trade-off assessments.

Key deliverables from the Solid Waste Management element will be a series of mission-specific design packages containing detailed process flow diagrams and supporting specifications and documentation. The detailed process flow diagrams will describe each optimized design of the automated subsystem. These diagrams will identify both the individual unit processes contained within the complete subsystem and the interconnections between these unit processes that are necessary to supply the required solid waste management operations.

Each solid waste management subsystem must be integrated with other P/C CLLS subsystems and possibly with a bioregenerative life support system for food production. An additional objective of the Solid Waste Management element is the definition of the subsystem interfaces for each design and the development of a thorough understanding of the accompanying interactions. The interfaces with other subsystems will be shown on the detailed process flow diagrams and described in accompanying documentation.

Automated operation and continuous monitoring of subsystem performance are requirements for long-duration missions. An additional objective of the Solid Waste Management element is the development of an optimum automatic control and continuous monitoring strategy for each design. Sensor and stream analyzer requirements will be defined and incorporated in the detailed process flow diagrams and accompanying specifications. Feedback will be provided for the Monitoring and Control Instrumentation element (WBS 1.3.1) and Systems Control Strategy element (WBS 1.3.2) to insure that each optimum control strategy is compatible with overall automation of the corresponding P/C CLLS system. This feedback will include definitions of those sensors and analyzers which require further development.

Within the context of this five-year project plan, the final objective of the Solid Waste Management element is to initiate the design, construction, and testing of one or more mission-specific subsystem prototypes. Each design package will contain a complete set of detailed process flow diagrams and the supporting documentation of interface and control/monitoring requirements that will provide the design basis for each prototype. Subsystem testing and further development at the prototype level will be followed by extensive performance evaluations of integrated P/C CLLS systems in a human-rated, ground-based test bed. The results of these ground-based evaluations will provide the basis for the design and fabrication of flight test hardware for detailed studies in space-based test beds. The objectives and technical approach for these subsequent tests are described in the System Tests element (WBS 1.4.5) and Human-Rated Tests element (WBS 1.4.6) of this project plan.

2.4.4.2 Technical Approach

Little data has been collected which characterizes the different solids-intensive waste streams found in previous space missions. Some effort was made to characterize both human waste streams for the Apollo missions and the specific content of Shuttle trash for one mission. Contractor efforts for specific space mission projects have estimated the content and production of some wastes (e.g. experiment-derived waste for the Space Station Life Sciences Laboratory). However, no coordinated effort has been made to characterize all of the potential waste streams for long-duration space missions.

In previous missions, solid wastes have been handled primarily through techniques of compaction, stabilization, and preparation for return to earth This approach is also the current solid waste management subsystem plan for Space Station. The storage and return to earth scenario will not be applicable to extended duration missions such as the establishment of a lunar base or a human mission to Mars. Instead, the solid waste management subsystem must be highly integrated with the other life support subsystems in a true closed-loop mode and must be designed to produce an absolute minimum of rejected residual material.

Some technologies have been proposed for destruction of solid wastes generated during long-duration missions (eg. pyrolysis, plasma oxidation, incineration, etc.) . However, none of these technologies have been systematically evaluated at the process, subsystem or system levels for their applicability to the solid wastes that might be produced during such missions. The problems of integrating these technologies with other P/C CLLS subsystems has also received little systematic study.

The design criteria for the solid waste management subsystem will be mission-dependent. On a Mars sprint-type mission, these design criteria will probably center around minimization of expendables, weight, power, and volume. On extended missions such as those involving base-related operations, the minimization of expendables may not be as important a criterion if the rejected residual solid is small, chemically and biologically inert and a suitable waste storage site is found. Instead, recycling may become a more important criterion such that resupply missions are minimized (especially in the case where a biological food production subsystem is present). Base-related operations might also strive to maximize the use of in-situ resources. These differing design criteria will govern the selection of suitable technologies for solid waste management in an integrated P/C CLLS system.

The development of optimized designs for automated solid waste management subsystems will require the identification and characterization of potential input streams, the identification and evaluation of technologies for processing and recycling and the definition of interfaces with other P/C CLLS subsystems including those associated with a bioregenerative subsystem for food production. The results of the foregoing efforts must be coupled with design criteria that are based on mission-specific requirements which apply to the integrated P/C CLLS system. Designs for candidate solid waste management subsystems must then be developed, evaluated and optimized through the combined use of subsystem and system analysis as well as input from supporting laboratory work and testing of breadboard prototypes.

The approach to achieving the objectives of the Solid Waste Management element will be based on a Work Breakdown Structure that consists of the following six sub-elements:

1.1.4.1 Waste Composition and Definition
1.1.4.2 Waste Handling and Processing
1.1.4.3 Product Recycling
1.1.4.4 Subsystem and System Analysis
1.1.4.5 Subsystem Test
1.1.4.6 Plant Interface

All of the above sub-elements will contribute to the development and selection of optimized solid waste management subsystem designs to serve future human missions. Of these, Subsystem and System Analysis is the key sub-element that provides guidance for, and receives feedback from the work conducted under the other sub-elements.

2.4.4.3 Description

The following is a summary of the work to be done in each sub-element of the Work Breakdown Structure (WBS) for the Solid Waste Management element. This work includes literature surveys, computer modeling, laboratory experiments, design evaluations and some breadboard testing of hardware, instrumentation, and control concepts.

It is recognized that dealing with solid wastes in one-g might be significantly different than handling solids in a less than a one-g environment. The work proposed in this section will concentrate on developing a full body of information, designs, and results in a one-g environment with attention paid to possible problem areas when addressing a less than one-g scenario.

WASTE COMPOSITION AND DEFINITION (WBS 1.1.4.1)

The characterization of potential waste input streams to the solid waste management subsystem will employ literature surveys, computer modeling techniques, and laboratory testing. A literature survey of the potential waste feed streams will be performed. The production rate and constituent composition of these waste feed streams in an integrated P/C CLLS system will be modeled, first as discrete streams and then as integrated streams. Discrete streams are defined as one-source input streams such as a single human or one experiment. Integrated streams are any combination of discrete streams (eg. human waste and waste from experiments). The capability to model discrete and integrated input waste streams is essential to any systematic analysis of a solid waste management subsystem. Where quantitative information is not available, trend information will be developed for use in Subsystem and System Analysis.

Both discrete and integrated streams that are characterized as "hazardous waste streams" will warrant special attention. Hazardous waste streams are defined as those streams that are ignitable, corrosive, or toxic to humans, animals, or plants. Characterization of these streams will be performed based on the outline of potential science experiments identified by Code OEXP, potential inputs from the space vehicles themselves and inputs from other subsystems in the P/C CLLS system.

Laboratory experiments will be conducted to validate the models of discrete and integrated waste streams and to obtain data for those waste feed streams where literature surveys show information to be lacking. A complete material balance basis will be developed for each potential waste stream. This information will be provided as an end deliverable of this task and will be used in the design development and evaluation work to be performed for the Subsystem and System Analysis sub-element.

WASTE HANDLING AND PROCESSING (WBS 1.1.4.2)

Separation, stabilization, treatment, reclamation or storage of a solid waste may entail its destruction, conversion to another more desirable product, and/or compaction to minimize the final residual volume. Each of these generic operations can be characterized by physical, chemical or biological processes. A literature survey will be performed to develop information on potential technologies for use in the solid waste management subsystem. The initial focus of this literature survey will be that of identifying a broad base of technology candidates for further screening. Wherever possible, the literature survey will attempt to accumulate fundamental process data (reaction kinetics, thermal efficiencies, etc.) that can aid in subsequent screening.

The handling of solid waste within an integrated P/C CLLS system will involve transferring solids-intensive and/or totally solid streams of material to the solid waste management subsystem. The literature survey of potential technologies will also be directed toward identifying solids handling processes and hardware which may be particularily suitable for use in a P/C CLLS system.

On long-duration missions, hazardous waste streams must be isolated, contained and subsequently processed to destroy them or convert them into benign products for either recycling or ultimate disposal. Currently, research on hazardous waste treatment has received much attention in the commercial sector. The literature survey will cover published information from commercial hazardous waste treatment R & D with the intent of identifying technologies and techniques that may be suitable for use in the solid waste management subsystem of an integrated P/C CLLS system.

An attempt will be made to translate the most promising technologies into preliminary, conceptual hardware that is suitable for use in a space mission-oriented P/C CLLS system. This effort is expected to lead to the definition of both follow-on experiments for supplying needed or absent data and breadboard prototype designs which are worthy of further testing. The follow-on experiments will be conducted under this sub-element of the Solid Waste Management element. Breadboard prototype development and testing will be conducted under the System Tests sub-element.

The results of the literature survey will be organized, evaluated and published in a set of comprehensive reports. These reports will also contain the conceptual hardware designs that will be developed for the most promising technologies. Separate reports will be prepared and published on the follow-on experiments. These reports will be primary inputs to the detailed design development and evaluation work conducted under the Subsystem and System Analysis sub-element.

PRODUCT RECYCLING (WBS 1.1.4.3)

Recycling of products derived from the solid waste management subsystem is highly desirable. This approach will minimize or possibly eliminate the need to dispose of residual material. A high degree of recycling is feasible if the solid waste management subsystem employs technologies that convert solids primarily to simple, benign species such as CO_2, water and elemental carbon.

Work conducted for this sub-element will focus on defining the most feasible recycling options for individual mission scenarios. Information developed under the System Requirements element (WBS 1.4.1) will be used to formulate the initial options. These initial options will be further refined by considering their match with the most promising technologies identified under the Waste Handling and Processing sub-element.

The deliverables from this sub-element will consist of a set of options and recommendations for product recycling that are applicable to each mission scenario that is defined by OEXP.

SUBSYSTEM AND SYSTEM ANALYSIS (WBS 1.1.4.4)

a. Model Development & Design Evaluations

The first phase of this task will be the utilization of a preliminary computer simulation model for each candidate waste processing technology that can be identified at the start of the work. Gaps in the supporting database and other related questions will be defined during the initial studies with each model and will be used to formulate the scope of the follow-on studies to be conducted as part of the work for the Waste Handling and Processing sub-element. Assumptions, estimates and analogies will be employed to the extent necessary to fill the gaps in the database and thereby enable the performance of subsystem analysis with a preliminary model of each waste processing technology. Since the individual candidate technologies will vary widely in state of knowledge and development, the corresponding preliminary models will differ in terms of sophistication at this stage of the work.

Input on mission-specific requirements for the solid waste management subsystem will be drawn from the System Requirements element (WBS 1.4.1) and used to formulate a series of preliminary designs. A computer simulation model of each preliminary design will be synthesized by combining the preliminary models of the individual waste processing technologies. Preliminary design evaluations will be conducted with each of the synthesized simulation models to quantify the impact of known estimates and assumptions. Where applicable, the initial subsystem models will include preliminary definitions of the requirements for interfacing with a bioregenerative life support system.

The computer simulation models for the series of mission-specific designs will evolve continually as work proceeds under both the element and the other P/C-related elements. This process of evolution will include increased refinement and sophistication in the models of the waste processing technologies as estimates and assumptions in the database are replaced by more precise information derived from follow-on experiments and testing of breadboard prototypes.

During the evolution of each subsystem model, a point or multiple points will be reached where a degree of validation becomes necessary. This process of validation will require some experimental work on a portion of the subsystem to determine if the performance predicted by the model matches that observed in actual operation. The procedure to be followed for validation and verification will be that developed under the Validation and Verification element (WBS 1.4.4). Experimental work required for model validation and verification will be conducted under the Subsystem Tests sub-element of the Solid Waste Management element.

Numerous trade-off and performance studies will be conducted with the evolving simulation models of the solid waste management subsystem. An initial reduction in the number of alternative designs for a specific mission will be accomplished without complete validation of the associated models. However, only validated computer simulation models will be used for studies that lead to the choice of an optimized design for each mission-specific subsystem. Once the choice of an optimized subsystem design has been made, the associated simulation model will be used for further studies to support the preparation of the corresponding design package.

Continual information flow to and from other elements will be necessary in the course of the work required to arrive at each optimized, mission-specific design for the solid waste management subsystem. Key elements in this process will be the Systems Monitoring and Control Instrumentation element (WBS 1.3.1), the Systems Control Strategy element (WBS 1.3.2), and the System Analysis Assessment element (WBS 1.4.3). Of these, the Systems Analysis and Assessment element will insure that each optimized design has been developed with full consideration of both the interfacing and control strategy requirements.

Work in FY90 will concentrate on the utilization of simulation models for the waste processing technologies and the accompanying definition of database requirements. The synthesis of subsystem models and the evaluation of the associated designs including model validation will occur in FY91 and FY92. Final design optimization studies and the transition to supporting simulations for preparing the design packages will occur in FY92 and FY93. Further refinement and upgrading of the subsystem design simulation models will occur beyond FY93 in support of the assembly and testing of the mission-specific prototypes.

b. Design Package Preparation

This task will cover the necessary work for preparing the primary deliverable from the Solid Waste Management element. A design package will be prepared to describe the optimized design of an automated solid waste management subsystem for each specified mission. Each design package will consist of detailed process flow diagrams and documentation to describe both the accompanying control and monitoring strategy and the interfaces with other subsystems to be employed in the given mission. Each process flow diagram will contain mass and energy balance summaries that will aid in addressing the subsystem efficiency and degree of closure mass recycling loop. Also, the process flow diagrams will describe the individual components of each waste processing technology used in the subsystem as well as the interconnections and control/monitoring elements for each technology. Finally, each design package will include the validated subsystem models used in preparing the process flow diagrams and accompanying supporting information.

The number of design packages to be prepared as deliverables will depend upon the number of distinct mission scenarios defined by the System Requirements element (WBS 1.4.1). The detailed contents and format of these design packages will adhere to the agreements reached by the participating NASA R & D and development centers (See Section 1.5).

Computer simulation work for this task will consist of those studies with validated models that may be necessary to develop supplementary information for the design packages. Changes in these models that may be necessary for this work will be implemented under the above-described Model Development and Design Evaluations task.

Work on the preparation of the design packages will begin in FY92 and build to a peak effort in FY93. Follow-on work in the form of design package revision and upgrading will continue after FY93 as work proceeds on the assembly of mission-specific prototypes.

SUBSYSTEM TEST (WBS 1.1.4.5)

a. Preliminary Tests — Partial Subsystems

Work under this sub-element will consist of both the experiments required for verification and validation of the simulation models and the studies of prototype hardware for waste processing technologies that were defined during the work conducted under the Waste Handling and Processing sub-element. These studies will be conducted on laboratory-scale prototypes or small-scale partial subsystems.

The prototype hardware studies will be performed to determine if promising technologies identified in literature surveys can be adapted to the constraints imposed by long-duration space missions. These studies are not intended to substitute for more complete testing of mission-specific prototypes in the event that certain of these promising technologies are employed in the optimized designs of the solid waste management subsystem.

The scope of each set of experiments for model validation and verification will be determined during the work for the Subsystem and System Analysis sub-element. It is expected that these requirements will depend upon the nature of the individual, mission-specific designs for the solid waste management subsystem. The resulting experiments will focus on only those portions of the subsystem that will confirm the predictions of each simulation model and are not intended to substitute for more complete testing of mission-specific prototypes.

The initial prototype hardware studies will begin in late FY90 and carry forward into FY91. The work on the validation and verification tests will be conducted in FY91 and FY92.

b. Test Subsystem Prototypes

This work is expected to begin in FY94 and continue through FY96. The objectives and approach will follow that outlined in the System Test element (WBS 1.4.5).

c. Integrated P/C Test Bed Studies

Tests of this type are expected to begin in FY97 and continue beyond FY98. The work will adhere to the objectives and approaches described in the System Test (WBS 1.4.5) and Human-Rated Test (WBS 1.4.6) elements.

PLANT INTERFACE (WBS 1.1.4.6)

Solid waste management will differ in the presence of both plant experiments and bioregenerative life support subsystems. Biological components will provide both a source and a sink of solid waste. This interface is particularly important when considering extended duration missions. An evaluation of this interface will be developed using information from both the literature and specific findings from work performed under the CELSS program. The thrust of this evaluation will be to define changes in the design criteria for the solid waste management subsystem that occur as a result of the presence of plant-based subsystems. These design changes will be summarized and communicated to the Subsystem and System Analysis sub-element for use in developing subsystem designs for those mission where plants will be present.

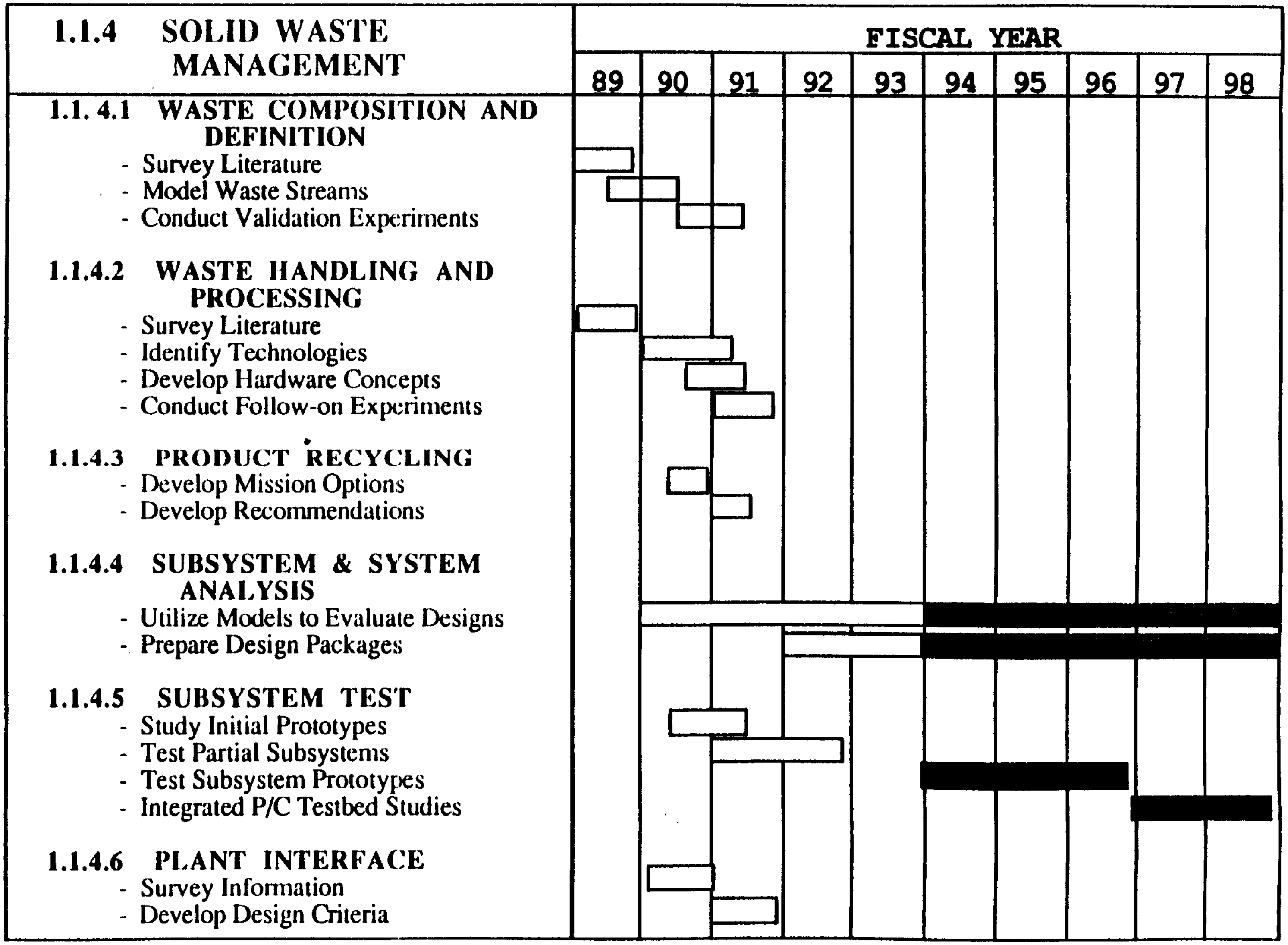
Work on this sub-element will begin in FY90 and carry through to the end of FY91.

2.4.4.4 Schedule

Figure 2.4.4-1 is an activity schedule for the Solid Waste Management element that begins with FY89 and extends through FY98. The foregoing descriptions of work under each sub-element of the Work Breakdown Structure cover only the projected activities through the end of FY93. However, it will be necessary to extend certain elements beyond FY93. In the case of the Subsystem Tests sub-element, there will be a transition to testing of mission-specific prototypes and evaluation of subsystems in integrated P/C Test Beds. The solid lines in Figure 2.4.4-1 show both the expected extensions of existing activities and the new transition activities that will start after FY93. A task flowsheet for development of P/C CLLS systems is provided in Technical Section 1.7 of this project plan.

2.4.4.5 Milestones/Deliverables

Figure 2.4.4-2 lists the major milestones and deliverables for the sub-elements in the Work Breakdown Structure of the Solid Waste Management element. Of these, the most important milestones are those for the various stages of the work for the Subsystem and System Analysis sub-element. The final design packages prepared under this sub-element constitute the primary deliverables from the Solid Waste Management element. Each of these design packages will describe an optimized, automated, mission-specific subsystem for solid waste management.


1.1.4 SOLID WASTE MANAGEMENT
FISCAL YEAR
89
90
91
92
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97
98
1.1.4.1 WASTE COMPOSITION AND DEFINITION
- Survey Literature
- Model Waste Streams
- Conduct Validation Experiments
1.1.4.2 WASTE HANDLING AND PROCESSING
- Survey Literature
- Identify Technologies
- Develop Hardware Concepts
- Conduct Follow-on Experiments
1.1.4.3 PRODUCT RECYCLING
- Develop Mission Options
- Develop Recommendations
1.1.4.4 SUBSYSTEM & SYSTEM ANALYSIS
- Utilize Models to Evaluate Designs
- Prepare Design Packages
1.1.4.5 SUBSYSTEM TEST
- Study Initial Prototypes
- Test Partial Subsystems
- Test Subsystem Prototypes
- Integrated P/C Testbed Studies
1.1.4.6 PLANT INTERFACE
- Survey Information
- Develop Design Criteria

Figure 2.4.4-1

Figure 2.4.4-2

Solid Waste Management
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.1.4.1 WASTE COMPOSITION AND DEFINITION					
• Literature survey complete	Δ				
• Waste Streams Modeled		Δ			
• Experiments Complete			Δ		
1.1.4.2 WASTE HANDLING AND PROCESSING					
• Literature Survey Complete	Δ				
• Technologies Identified			Δ		
• Hardware Concepts Defined			Δ		
• Experiments Complete			Δ		
1.1.4.3 PRODUCT RECYCLING					
• Mission Options Developed			Δ		
• Recommendations Developed			Δ		
1.1.4.4 SUBSYSTEM & SYSTEM ANALYSIS					
• Prelim. Technology Models		Δ			
• Prelim. Subsystem Designs			Δ		
• Prelim. Subsystem Models			Δ		
• Validated Subsystems Models				Δ	
• Mission-Specific Designs				Δ	
• Designs Optimized					Δ
• Design Packages Complete					Δ
1.1.4.5 SUBSYSTEM TEST					
• Initial Prototypes Tested			Δ		
• Validation Experiments Complete			Δ		
1.1.4.6 PLANT INTERFACE					
• Information surveyed		Δ			
• Design Criteria Complete			Δ		

2.4.5 Food Management

Food management subsystems and technology are not currently part of either the OAST or the OSSA programs in life support systems. Development of this technology is mandatory in order to carry out many of the proposed long-duration missions now under consideration by OEXP.

2.4.5.1 Objectives

A critical objective for near term work on advanced life support systems is the research and development of appropriate space food systems which will provide crew members with appetizing, safe, nutritious and convenient food. This objective must be achieved within many critical biological, operational, behavioral, and engineering constraints. Future efforts planned under the six sub-elements of this technical element will strive to meet mission requirements while working within these constraints. Specific emphasis will be placed on deriving and understanding both the human and the mission-specific requirements for the food management subsystem.

2.4.5.2 Technical Approach

A food management subsystem consists of food, its package, and all component equipment used to preserve, prepare, and serve food for the consumer. Space food subsystems require, in addition, accurately defined limits for safety, acceptability, nutritional content, weight, volume, storage stability, and ease of preparation. Space food subsystems must be designed by using a systems analysis approach which first divides the subsystem into manageable units, then identifies the problems, alternative solutions, and benefit/risk ratios involved in each unit of the entire subsystem. This plan attempts to apply this kind of a systems analysis approach to the development of a new space food system to support long-duration space missions.

New food subsystems (including unconventional foods such as those derived from chemical synthesis) must be developed to support space based personnel on long-duration advanced space missions with consideration given to the special needs of a culturally heterogeneous crew, more extreme variations in workload (e.g., from rigorous EVA construction to a prolonged sedentary Mars transit), as well as on-board requirements for food production and waste recycling. Achieving crew satisfaction with space food requires that changes in normal dietary regimens are made in accordance with established food habits and values. Food habits depend not only on availability, but also on a complex combination of biochemical and psychological factors, including metabolic needs, cultural patterns, religious practices, individual conditioning, and mental attitudes about the consumption of food produced from recycled waste products.

High quality food has been traditionally used as a morale builder on isolated, confined missions. In partially and fully closed-loop space food subsystems, the weight and volume of the food supply will be critically limited. Therefore, food and its consumption must be carefully planned to meet both physiological and psychological needs. Key human factors in planning for advanced food systems go beyond nutritional needs to include definition of habitability and quality of life requirements; psychological and cultural considerations; and on-board support equipment design concepts that can produce the required food. New methods of training and orientation are needed which will give crew members a working understanding and sensitivity to their roles in, and critical impacts upon, autonomous and semi-autonomous space food ecologies.

The production of space foods during a mission will have important psychological implications and will probably offer unique benefits in terms of enhancement of feelings of control over the environment. Growing plants for food in space has already proven to offer crew members genuine psychological support under the stressful conditions of prolonged spaceflight. Cosmonaut Lebedev, who had never been fond of tinkering in the garden on Earth, became fascinated with caring for the ten different kinds of plants grown on a 1982 Russian mission: wheat, oats, peas, borage, radish, onion, parsley, coriander, dill, and carrots. Not only did Lebedev conclude that *"Without plants, long-duration space missions are impossible"*, but, he went on to state: *"This was the first time I felt a fascination in contact with plants. You sit down in your free time and watch them--they appear to be growing in front of your very eyes. . . It is natural for man to busy himself with living things, and necessary for him to follow up his efforts."*

Closing the loop for extended space missions is a function of the economics of transportation versus regeneration. Depending upon the specific conditions and costs of a given mission, too heavy a reliance on either method may be shown to be cost prohibitive or otherwise nonfeasible. However, the critical needs for system redundancy and production efficiency argues for the inclusion of unconventional food regeneration schemes. The current state of knowledge in this area is limited at best. Comprehensive research in each of the sub-elements shown in the following Work Breakdown Structure is required in order to arrive at a set of mission-specific food requirements and designs of adequate regeneration subsystems. The specific sub-elements are discussed in the following sections:

1.1.5.1 Dietary Logistics
1.1.5.2 Food Synthesis
1.1.5.3 Processing Technology
1.1.5.4 In-Situ Resources
1.1.5.5 Subsystem and System Analysis
1.1.5.6 Subsystem Test

2.4.5.3 Description

The description of the approaches to support the objectives includes literature surveys, laboratory testing, analytical modeling techniques, test bed demonstrations, and updates on the state-of-the-art, particularly in the areas of biotechnology where much of the current information is proprietary. A systems approach will be used to ensure that all components involved in the development of the food subsystem are included.

DIETARY LOGISTICS (WBS 1.1.5.1)

Human physiological requirements for food on extended duration space missions will be measurable not in food units, but rather in terms of nutritional needs. All potential on-board production and synthesis subsystems have in common the requirement to meet the nutritional needs of human beings. Crew nutritional needs will not be easily calculable from normal baseline measures, but rather are dependent on a number of critical factors, especially metabolic levels relative to energy output (e.g., related to workload).

It is commonly assumed that all human nutritional factors are known. But, so far, no actual test has been undertaken of an individual fed for very long periods of time on highly purified and largely synthesized materials. The possibility that as yet unknown trace elements or organic compounds may be essential for life must be considered.

In closed systems, there exists the added danger of toxicity at high levels of nutrient elements or the accumulation of toxic substances. For instance, there is often a narrow tolerance between the minimum requirement level of micronutrients and the toxic level. Restricted diets and recycling also tend to accumulate toxic substances such as antibiotics, pesticides, mycotoxins, and corrosion products from storage containers and components of the recycling subsystem. Research is needed to gain a better understanding of requirements and tolerances, as well as to develop an efficient on-board monitoring and sensor systems to keep track of trace nutrients and toxic substances in recycling operations.

The acceptability of individual foodstuffs, as well as of overall dietary regimens, is not solely dependent on sensory properties. Acceptability is largely dependent upon conditioning, habits and value systems, and internal chemistry. The ideal space diet probably lies somewhere between a basic sustenance level diet and one which provides a tremendous variety of preference foods which would be difficult to produce in a small, closed ecological subsystem.

In addition to the basic requirement of protection for storage, packaging of space food will hold tremendous implications for perceived palatability of foodstuffs and overall acceptance by the crew. Packaging produces a complex set of reactions in the mind of the beholder, all of which contribute to a feeling about the produce inside. Research is needed in the area of defining guidelines for appropriate (appetizing) packaging of space foods in order to gain the maximum satisfaction and crew acceptance.

The integration of the unique customs and traditions associated with different cultures will be enhanced through the sharing of food and foodways in "feasting" on-board. This sharing is a critical element in the development of space food systems for an international space mission, and research is planned in this area, as well as in the area of religious prescriptions and proscriptions about food which will also shape the ultimate satisfaction of the crew members with the food subsystem.

FOOD SYNTHESIS (WBS 1.1.5.2)

In a closed ecological system, a vital aspect of the recycling process is the synthesis of raw materials into food. Raw materials include both macronutrients (protein, carbohydrates, and lipids), as well as micronutrients (vitamins and minerals). These raw materials can be acquired from a variety of sources, such as locally grown plants, local production of microbial or cell derived nutrients, on-board chemical synthesis of food, derived nutrients, or from stored or periodically resupplied essential nutrients not readily produced within the habitat. Conversion of these nutrients into acceptable, safe, and nutritious foods will require a major research effort. Biotechnology processing techniques offer a unique approach for the conversion of raw materials into edible foods with a minimum expenditure of energy and labor. By transferring genes from one organism to another, biotechnologists are able to program microbes and plant cells to produce different products, change the functionality of a protein, or produce an enzyme to convert one material to another. An example of this which is being used in industry today is the production of the enzyme rennin from yeast for use in making cheese.

Another approach is to develop cellular biology methods for the production of plant material to be used for food. For crops in which only the vegetative parts are eaten, such as lettuce, carrots, celery, etc., seed production is an additional step, which could be eliminated with a savings in space, energy, and labor. Using cell biology techniques such as somatic embryogenesis and root/shoot organogenesis, edible portions of fruit and vegetables can be produced without the time and energy consuming steps associated with food production. These techniques are currently being developed and used for Earth based food production. A system for vegetative cellular food production will require concrete knowledge concerning the Earth based research being undertaken. Information on the subject is scarce since most of the research being done is highly proprietary. An immediate research task is to determine the status of current research and development and the application to a controlled ecological life support system (CELSS).

Physical/chemical means may also be used to synthesize food from feedstock derived from recycled material produced by other on-board life support subsystems. NASA has already during space flight, as well as methods for its prevention, remains unknown. Experimental methods for ameliorating bone loss have shown some effect, including exercise protocols, compressional suits (e.g., the Soviet's "Penguin Suit"), and thyrocalcitonin administration. Dietary countermeasures, particularly reduction of proteins and elevated intake of diphosphonates, calcium, and phosphorus, may offer improvement. Analytical models must be developed to evaluate alternative methods to counteract physiological and human performance problems, such as bone loss, which result from extended exposure to microgravity.

SUBSYSTEM TEST (WBS 1.1.5.6)

Previous spaceflight experience has demonstrated that successful development, fabrication, integration, and testing of space food subsystems requires unique technical management efforts to establish and coordinate priorities between and within human and engineering considerations. This situation is exacerbated by several factors inherent to foods in general and especially foods for manned space flight.

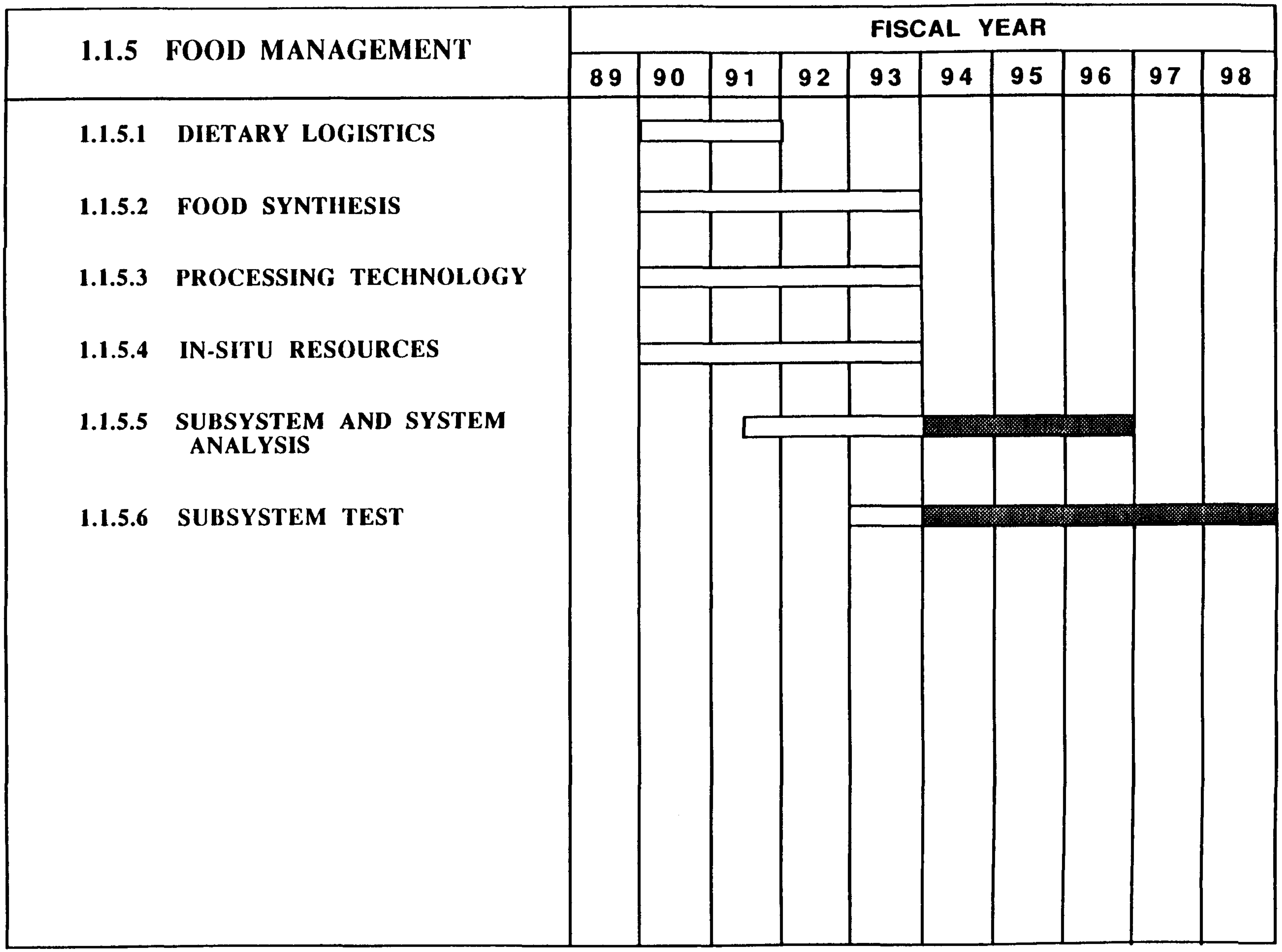
Experiments must be conducted to test each of the space food subsystem components for long-duration space missions. In response to the outcome of these component tests, practical considerations and adjustments must be made to ensure maximum efficiency of each mission-specific subsystem.

2.4.5.4 Schedule

Figure 2.4.5-1 is an activity schedule for the Food Management element that begins in FY89 and extends through FY98. It is anticipated that work on certain elements will be continued beyond the five years covered by this project plan. The expected continuations are shown as solid lines on the figure.

2.4.5.5 Milestones/Deliverables

Figure 2.4.5-2 is a preliminary list of the major milestones and deliverables for the sub-elements in the WBS of the Food Management element. Since no work on the Food Management element is scheduled for FY89, the first major milestones will not be reached until the end of FY90. Milestones for the System Test sub-element will be developed in FY90.


1.1.5 FOOD MANAGEMENT
FISCAL YEAR
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1.1.5.1 DIETARY LOGISTICS
1.1.5.2 FOOD SYNTHESIS
1.1.5.3 PROCESSING TECHNOLOGY
1.1.5.4 IN-SITU RESOURCES
1.1.5.5 SUBSYSTEM AND SYSTEM ANALYSIS
1.1.5.6 SUBSYSTEM TEST

Figure 2.4.5-1

Figure 2.4.5-2

Food Management
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.1.5.1 DIETARY LOGISTICS					
• Literature Survey		Δ			
• Nutritional Requirements			Δ		
• Acceptability Patterns			Δ		
• International Foods		Δ			
1.1.5.2 FOOD SYNTHESIS					
• Literature Survey		Δ			
• Biotechnology Feasibility				Δ	
• Plant Genetic Engineering					Δ
• Microbial Production				Δ	
• Physical/Chemical Production					Δ
1.1.5.3 PROCESSING TECHNOLOGY					
• Controlled Atmosphere Packaging					Δ
• Physical/Chemical				Δ	
• Biological/Microorganisms Enzyme Transformation				Δ	
1.1.5.4 IN-SITU RESOURCES					
• Literature Survey			Δ		
• Available Resources				Δ	Δ
• Application				Δ	
1.1.5.5 SUBSYSTEM AND SYSTEM ANALYSIS					
• Food Production Techniques Data Base			Δ		
• Nutritional Requirements			Δ		
• Dietary Countermeasures				Δ	
• Mission Scenarios					Δ

2.5 SYSTEMS CONTROL

Life support system operations aboard a spacecraft will involve a great many dynamic interactions. Waste generation will not be a continuous process, leading to time varying fluctuations in reprocessing needs within the system. Variations in crew exertion and rest cycles will result in time varying demands upon the life support system. Recycling equipment will periodically need to be turned on and off or have their continuous recycling rates changed. Various types of monitoring and control instrumentation and accompanying control strategies will be needed for effective operation of a P/C CLLS system. The P/C CLLS project will develop the systems control strategies and instrumentation configurations required for support of future long-duration space missions.

2.5.1 Systems Monitoring and Control Instrumentation

2.5.1.1 Objectives

The Systems Monitoring and Control Instrumentation (SMCI) element of the project involves requirements definition, technology assessment, hardware specification, prototype sensor and instrumentation development, and integration support for integrated mission-specific P/C Closed Loop Life Support (CLLS) systems. Specific technology sub-elements defined in the WBS and supported under the SMCI element include:

a. Integration (WBS 1.3.1.1)
b. Food (WBS 1.3.1.2)
c. Biological Contaminants (WBS 1.3.1.3)

In this effort, specific emphasis will be placed on creating a structured engineering program to address the particular requirements of integrated P/C CLLS systems, while consolidating common characteristics and providing a systems-oriented approach to sensor and instrumentation development and implementation.

Specific objectives of the SMCI element are:

1. Develop engineering specifications based on program, science, and technology requirements defined in the applications elements of the mission-specific P/C CLLS systems. These specifications will include measurement parameters and characteristics, operating protocols, subsystem and integrated system configurations, and logistics and constraints peculiar to the specific mission scenarios defined by OEXP.

2. Wherever possible, consolidate sensor and instrumentation monitoring and control requirements and define the optimum tradeoff considerations for system efficiency, accuracy, reliability and maintainability.

3. Serve as a focal point for work on monitoring and control instrumentation. Interface and coordinate instrumentation development with specific technology elements to ensure that monitoring and control requirements for those technologies are being adequately addressed.

4. Exploit advanced technology from related NASA R & D activities, and use industrial and academic developments to leverage available resources.

5. Coordinate with the Systems Control Strategy element (WBS 1.3.2) on the development of mission-specific systems control and automation strategies which take into account monitoring and measurement requirements, as well as advanced automated control technology. Using critical monitoring and control requirements defined in the Water Management, Air Revitalization, and Solid Waste Management elements, select and implement instrumentation systems to validate procedures and algorithms developed under the Subsystem and System Analysis sub-elements. Use resultant data and information obtained to specify the next phase in development of the required integrated P/C CLLS measurement systems.

2.5.1.2 Technical Approach

INTEGRATION (WBS 1.3.1.1)

The basic strategy will be to initially baseline planned Space Station ECLSS system specifications, and to use those specifications as a point of departure for defining monitoring and instrumentation requirements for the SMCI element. Space Station preliminary IOC plans currently call for a partially closed-loop, Physical/Chemical life support system. Due to the extended duration and long distances involved in potential Pathfinder missions, automated closure of the life support systems control and monitoring loop must be accomplished to the maximum extent possible. This requirement will involve development and incorporation of advanced control system techniques, and the concomitant use of accurate, stable, real-time sensors and instrumentation systems. A high degree of specificity and system consolidation will minimize the interface concerns required for implementation of these advanced monitoring and control instrumentation systems.

Specific attention will be placed on distinguishing between requirements for monitoring and control instrumentation. Sensor systems which must function within a control loop must be responsive, accurate, and sensitive to the parameters of interest. Monitoring instrumentation can be somewhat more general in nature, and should serve as a form of quality control and reference for assessing the performance of the more automated systems. Tradeoff analyses will be conducted to ascertain the proper technology for a given application.

A modular, fault-tolerant development approach will be employed. Instrumentation components and subsystems which have common or similar functions and can support multiple applications will be identified and developed. In addition to optimizing the efficiency of the engineering development process, this approach will minimize logistical problems caused by the need for back-up and redundancy should in-flight repairs or modifications become necessary on a given mission.

Within this sub-element, core integration functions including planning, prioritization, consolidation, and interface activities will be conducted. Systems engineering and advanced technology development requirements will also be accomplished. Systems engineering tasks include:

- Sensor, instrumentation development
- Hardware configuration management and documentation
- Data management
- Automatic control systems
- Interfaces
- Test, calibration, and certification

A requirements analysis and technology assessment will identify and prioritize the work to be done for the SMCI sub-element.

FOOD (WBS 1.3.1.2)

Since food requirements are not clearly defined within the context of an integrated P/C CLLS system, SMCI efforts in this area will be given a low priority. General requirements for food quality, processing efficiency, and biological/microbial control will be explored, and the potential application of bio-regenerative food supply technology will be considered. A close relationship with technology and SMCI requirements for CELSS will be maintained and exploited wherever possible. Any instrumentation requirements delineated in the Food Management element (WBS 1.1.5) will be addressed.

BIOLOGICAL CONTAMINANTS (WBS 1.3.1.3)

SMCI activities in this area will support requirements in all of the P/C CLLS technology elements, and will encompass requirements for identification, collection, and processing of biological contaminants. Advanced and emerging developments in biotechnology will be applied to SMCI requirements for water, air, and solid waste processing to increase the efficiency and effect the desired automation and closure of integrated P/C CLLS systems.

2.5.1.3 Description

It is recognized that sensor location in a less than 1-g environment may be significantly different than in a ground based environment. This is especially true for sensors that will be monitoring/measuring a medium where more than one phase is involved. The following work will concentrate on identifying sensor needs for a ground based environment with special attention dedicated to those measurement parameters that may differ in a low gravity setting.

INTEGRATION (WBS 1.3.1.1)

Real-Time P/C CLSS Sensor/Instrumentation Technology

Applications for measurement of parameters identified for integrated P/C CLLS systems include water quality monitoring, air revitalization, solid waste, food, and biological contaminants. Sensors based on chemical, biological, and ion-selective integrated circuit technology may allow for automated, real-time closed-loop monitoring and control of some parameters, and permit centralization of sensor and instrumentation systems, and control procedures. This element will evaluate technology requirements, define engineering approaches, investigate applicable technologies, develop specifications, and implement representative prototype measurement systems for consideration as candidates for inclusion in automated monitoring and control systems.

Work in FY 89 will focus on requirements definitions, technology assessments and initial development of system specifications. The technology assessment and specifications development activities will continue into FY 90. Instrumentation development will commence in FY 90 and continue through succeeding years along with appropriate testing and evaluation.

Chemical Composition Monitoring Technology

Emerging technologies for determination of the composition of complex mixtures containing possible unknowns include tandem mass spectrometry (MS/MS), Fourier transform infrared (FTIR), and frequency modulated infrared (FMIR). Combinations of these techniques and other more mature technologies with Artificial Intelligence (AI) techniques should provide the basis for automated monitoring and control of trace contaminants and other chemical products or by-products that are indigenous to mission-specific integrated P/C CLLS systems.. The work will include the identification of chemical species that are to be detected and monitored. Miniaturized prototype instrumentation will be developed and evaluated. The use of this instrumentation for automated control purposes will be evaluated and optimized in conjunction with ongoing work for the Systems Control Strategy element (WBS 1.3.2).

Work in FY 89 will concentrate on defining the requirements for chemical composition detection and monitoring and developing the specifications for application to mission-specific, integrated P/C CLLS systems. Refinement and completion of these specifications will occur in FY 90. Instrumentation technology assessment will commence in FY 89 with development to follow in FY 90. Testing, evaluation and refinement will begin in FY 91 and continue in succeeding years.

FOOD (WBS 1.3.1.2)

Instrumentation efforts in the P/C CLLS area will be limited to support for food quality monitoring, effected by periodic testing of representative samples. Measurement systems should permit testing for biological contaminants, and other extraneous chemicals which may be present in the sample. For bio-regenerative food processing systems, such as those identified for CELSS applications, sensors and instrumentation for closed-loop, continuous, automated measurement and control will be developed and evaluated in prototype configurations.

Work in this area will not commence until FY 91. At that time, sufficient progress will have been made under the Food Management (WBS 1.1.5) and P/C Bio Systems (WBS 1.4.2) elements to allow definition of the system control and monitoring requirements.

BIOLOGICAL CONTAMINANTS (WBS 1.3.1.3)

Emerging developments in biotechnology may permit the incorporation of genetically manipulated biological sensors which have application in P/C CLLS measurement systems. Such organisms as bacteria, fungi, and viruses may permit measurement of environmental contaminants. This element will explore the potential applicability of such biological sensors in a demonstration case.

Work on defining system requirements, assessing the technology and preparing specifications for application will begin in FY 90. Instrumentation development, testing and refinement will begin FY 91 and continue in succeeding years.

2.5.1.4 Schedule

See Figure 2.5.1-1

2.5.1.5 Milestones and Deliverables

See Figure 2.5.1-2

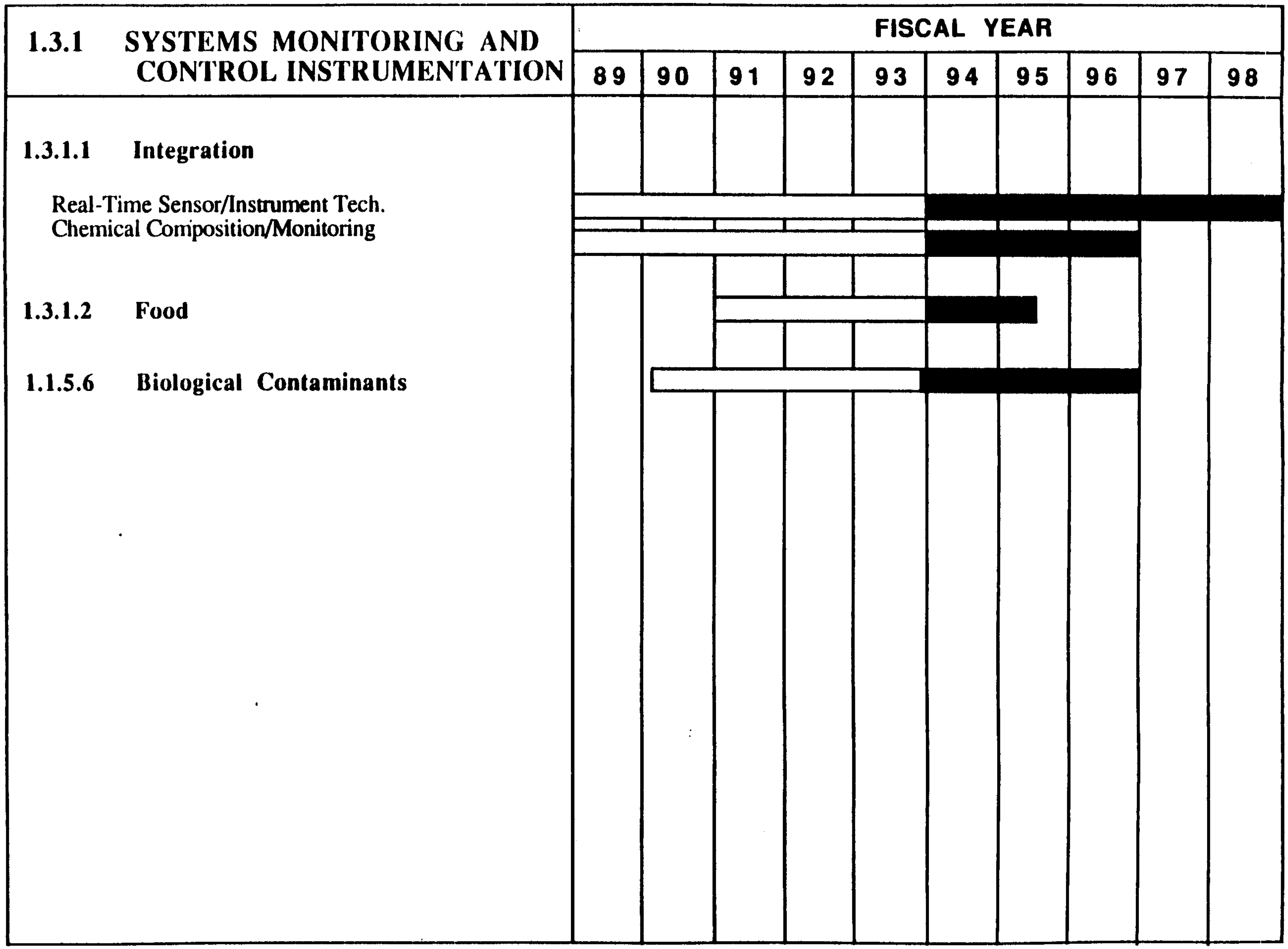

1.3.1 SYSTEMS MONITORING AND CONTROL INSTRUMENTATION
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.3.1.1 Integration
Real-Time Sensor/Instrument Tech.
Chemical Composition/Monitoring
1.3.1.2 Food
1.1.5.6 Biological Contaminants

Figure 2.5.1-1

Figure 2.5.1-2

Systems Monitoring and Control Instrumentation Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.3.1.1 INTEGRATION					
• Real-Time Sensor/Instr. Technology					
- requirements definition		Δ			
- technology assessment		Δ			
- system specification			Δ		
- instrumentation development				Δ	
- test, evaluate, iterate					Δ
- transition					Δ
• Chemical Composition/Monitoring					
- requirements definition		Δ			
- technology assessment		Δ			
- system specification			Δ		
- instrumentation development				Δ	
- test, evaluate, iterate					Δ
- transition					Δ
1.3.1.2 FOOD					
- requirements definition			Δ		
- technology assessment			Δ		
- system specification				Δ	
- instrumentation development				Δ	
- test, evaluate, iterate					Δ
- transition					Δ
1.3.1.3 BIOLOGICAL CONTAMINANTS					
- requirements definition		Δ			
- technology assessment		Δ			
- system specification			Δ		
- instrumentation development				Δ	
- test, evaluate, iterate					Δ
- transition					Δ

2.5.2 Systems Control Strategy

2.5.2.1 Objectives

Life support systems are inherently dynamic. Changing any one operating parameter will have a domino effect, causing downstream impact on the operations that must be performed by other equipment. While some attention has been given to subsystem process control, there has been little work directed towards development of optimized control strategies for integrated P/C CLLS systems.

The objectives of the Systems Control Strategy element are two-fold:

a. Provide the means for automated handling of operational instabilities within mission-specific P/C CLLS systems.

b. Minimize the impact of P/C CLLS operations and maintenance on the workload of the mission crew.

Strategies developed under this element will be utilized for integrated system control simulations of OEXP mission scenarios and in system tests to be conducted in research test facilities and human-rated test beds. Also, contacts will be established with instrumentation and control-related programs within OAST (Code RC).

2.5.2.2 Technical Approach

A range of events can lead to instabilities within an integrated P/C CLLS system. Some of these instabilities will be natural occurrences during a working day. These occurrences will include periodicities in the generation of wastes, and variations in crew exertion levels. If the mission includes experiments with laboratory animals and/or a bioregenerative life support system for food production, longer term instabilities can result from the plant and animal life cycles. Finally, major instabilities can be caused by other more catastrophic events such as equipment failures and accidents.

The full range of foreseeable operating contingencies must be identified as a first step in defining system control strategy requirements. The available control variables must be identified. Plans for resource allocations in response to specific situations must then be formulated.

Simple automation and control strategies often may not be sufficient. For example, unsophisticated control algorithms can cause unnecessary system shutdowns, mandating immediate manual take-over, with a resultant strain upon the crew. Recently, some thought has been given to the development of generic controller architectures using common logic frameworks and formats for use on Space Station. Efforts to create expert systems (e.g. for thermal control) using heuristics when quantitative or empirical models of control don't exist, are in the proof-of-concept stage. Man-machine interface work and control research is an on-going NASA effort. In such studies, the complexity of the task, and the level at which control will be implemented to autonomously operate is being investigated along with evaluations of the impact of human decisions and action in the control loop.

Two sub-elements have been defined to meet the objectives of the Systems Control Strategy element:

1.3.2.1 Autonomous Control
1.3.2.2 "Semi-Autonomous" Control

The Autonomous Control sub-element (WBS 1.3.2.1) will address the use of expert system and related heuristic software technologies for autonomous process control and control simulation. The Semi-Autonomous Control activity (WBS 1.3.2.2) will explore algorithmic process control methodologies.

2.5.2.3 Description

AUTONOMOUS CONTROL (WBS 1.3.2.1)

A preliminary requirements assessment identifying the type of functions to be supported by automated control of an integrated P/C CLLS system will be initiated in FY89 and completed in FY90. This preliminary assessment will categorize events that are: 1) housekeeping functions, 2) complex control scenarios descriptive of foreseeable normal and abnormal operating conditions, and 3) scenarios requiring active crew intervention. Desirable parameter characterization ranges for environmental variables will be developed and a preliminary assessment of possible control mechanisms prepared.

The preliminary assessment will be used in FY90 to guide the utilization of heuristic software for both process control simulation and for effecting actual control of process operations. An initial step in implementation will be a more rigorous evaluation of various types of control strategies (e.g. feedforward, feedback, adaptive, hybrids, etc.).

The environmental control variable defined in the preliminary assessment will be used to identify mission-specific monitoring and instrumentation requirements. These requirements will be defined as a joint effort with the Systems Monitoring and Control Instrumentation element (WBS 1.3.1).

Heuristically based software models of various system and sub-system level control scenarios will be designed in FY91 and evaluated in FY92 and FY93. Emphasis will be placed on the design and implementation of prototype control models that will be suitable for use in integrated system tests. The heuristic "expert system" software will be tailored to those types of control problems for which it is most suited. Both top level P/C CLLS management and problems of failure diagnosis and compensation are control problems that can benefit from use of heuristics. It is anticipated that some of the work for the Autonomous Control sub-element will be continued into the FY94 - FY98 time frame.

"SEMI-AUTONOMOUS" CONTROL (WBS 1.3.2.2)

"Semi-Autonomous Control" will address application of algorithm-based process control techniques to mission-specific, integrated P/C CLLS systems. Algorithmic technique utilization will provide support for the Autonomous Control sub-element (WBS 1.3.2.1). It is anticipated that algorithmic techniques will be most appropriately used in optimizing the operation of subsystems with efficiencies that vary over time. One example would be the optimization of adsorption and desorption cycles between multiple Solid Amine Water Absorption (SAWD) units contained within an integrated P/C CLLS system.

The identification of applications for algorithm-based control will begin in FY90 with completion scheduled for FY91. These applications will be drawn from the subsystem and systems analysis work conducted for the Thermal Control (WBS 1.1.1), Air Revitalization (WBS 1.1.2), Water Management (WBS 1.1.3) and Solid Waste Management (WBS 1.1.4) elements. Systems monitoring and control instrumentation needs associated with these applications of algorithm-based control will be developed as a joint effort with work conducted for the Systems Monitoring and Control Instrumentation element (WBS 2.5.1). It is anticipated that some of the "Semi-Autonomous" control work will also extend into the post - FY93 period.

2.5.2.4 Schedule

See Figure 2.5.2-1

2.5.2.5 Milestones and Deliverables

See Figure 2.5.2-2

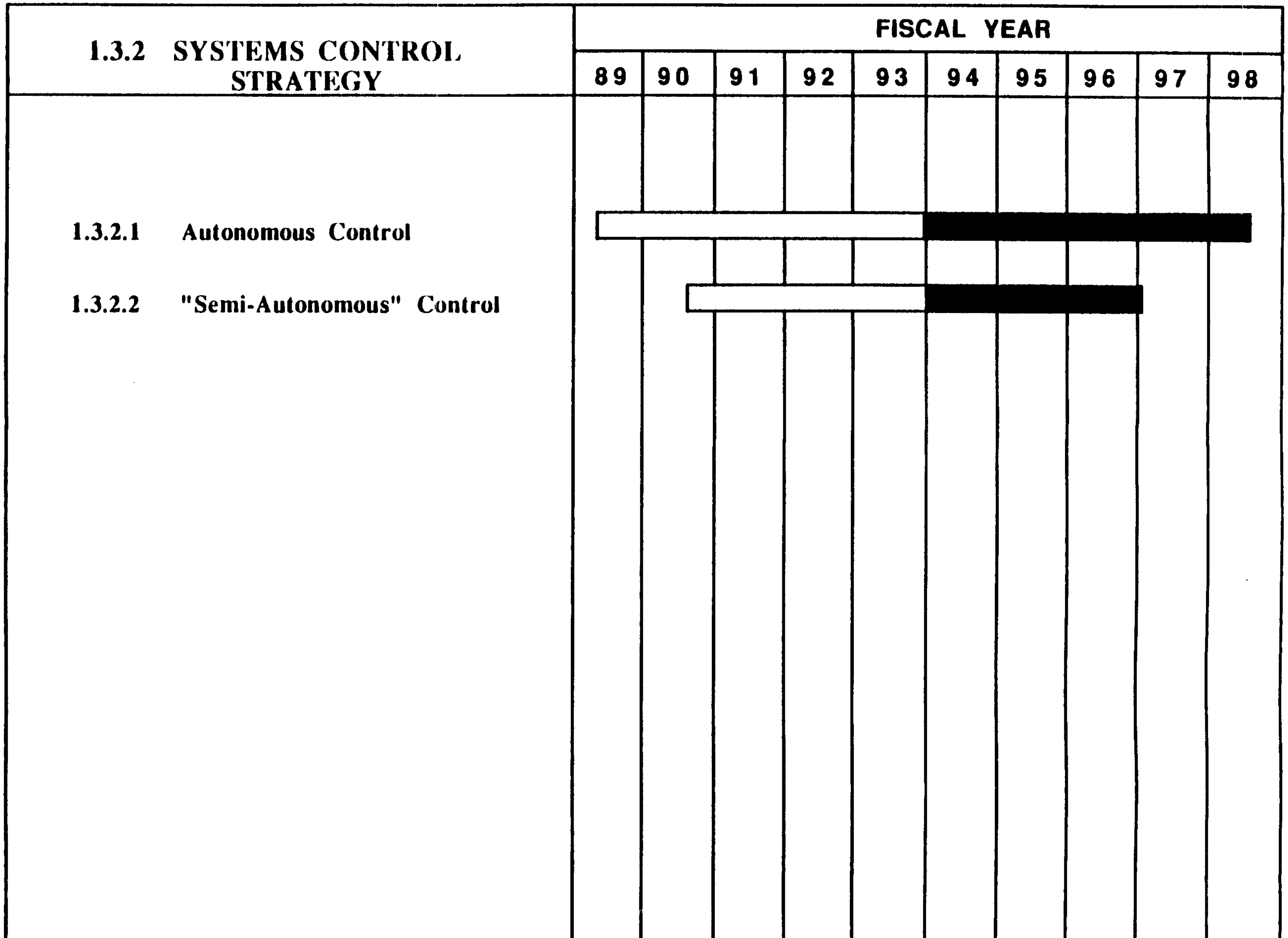

1.3.2 SYSTEMS CONTROL STRATEGY
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.3.2.1 Autonomous Control
1.3.2.2 "Semi-Autonomous" Control

Figure 2.5.2-1

Figure 2.5.2-2
Systems Control Strategy
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.3.2.1 AUTONOMOUS CONTROL					
• Control requirements assessment		Δ			
• Control model design			Δ		
• Scenario control model evaluation					Δ
1.3.2.2 "SEMI-AUTONOMOUS" CONTROL					
• Algorithm application identification			Δ		
• Incorporation into control models					Δ

2.6 SYSTEM INTEGRATION

System integration is commonly viewed as being the process of physically combining individual hardware components and/or functional hardware packages (i.e. subsystems) to provide a final assemblage or system that is designed to perform certain well-defined operations. However, this five-year plan is concerned primarily with R & D work that is intended to provide a P/C CLLS technology base which will meet the requirements of future, long-duration missions to be defined by OEXP. This R & D work emphasizes laboratory experiments for gathering basic data, simulation modeling for analysis of subsystem and system designs and evaluations of basic P/C technologies.

In view of this emphasis, the concept of system integration must be expanded to include the efforts that are necessary to organize and direct the R &D program. These efforts include the development of system requirements for mission scenarios, the examination of hybrid designs containing both P/C and bioregenerative subsystems and the performance of guidance-oriented, system-level analyses and assessments. The development of methodologies for model validation and verification and planning for future hardware tests are also part of the system integration effort for an R & D - intensive project of the type described in this plan.

2.6.1 System Requirements

2.6.1.1 Objectives

The demands to which a P/C CLLS system must respond are termed system requirements. These requirements are separate and distinct from the process and subsystem technologies that are integrated to form the P/C CLLS system itself. System requirements must be established before final designs for mission-specific, integrated P/C CLLS systems are developed.

An important system requirement is that of meeting the life support needs of the crew for O_2, food, potable water and prompt removal of wastes, including CO_2, human wastes and airborne particulates and volatiles. The system must also operate reliably and stably over extended periods of time, and it must function under the constraints of the space mission. Among the latter constraints are limitations of mass, volume, power and human labor. Additional constraints are imposed by the space environment and include variations in gravity and space radiation.

The objectives of the System Requirements element are to identify, organize and document both baseline and mission-specific requirements for a P/C CLLS system. The mission scenarios to be used will be developed by the Office of Space Exploration (OEXP), but will fundamentally include lunar use, transit to Mars, and use on Mars.

It is anticipated that the work for this element will establish a well-documented crew Physiological Database (PDB) that can be referenced in all P/C CLLS design and development work ranging from process modeling through the synthesis of integrated systems. This PDB will be supplemented by documented information on the crew's environmental requirements. Baseline and mission-specific envelope values will be established for parameters such as temperature, pressure and concentrations of O_2, N_2, CO_2, water vapor, particulates and trace contaminants. Also, the work will include the development of baseline and mission-specific constraints on mass, volume, power consumption, reliability, labor demand and frequency of resupply that apply to a P/C CLLS system.

2.6.1.2 Technical Approach

The System Requirements element (WBS 1.4.1) will examine both generic requirements and those requirements that are specific to long range missions being identified by OEXP. The approach taken will be to first identify baseline requirements that are not affected by mission scenario definitions. The baseline requirements will then be modified and adjusted to conform to specific missions scenarios.

Extensive databases exist on human physiological and metabolic data that have been compiled from ground-based testing and from in-flight measurements. This data, along with data on basic perturbations resulting from various human activity levels and resting periods, will comprise the Physiological Database (PDB). The PDB will include a range of data that reflects variations in both the physical size of individual crew members and the number of persons in the crew itself. The PDB will also include preliminary estimates of crew time availability for maintenance, science experiment operation and personal duties.

The crew's environment must be maintained within specific envelope values for parameters such as temperature, pressure and concentrations of O_2, N_2, CO_2, water vapor, particulates and trace contaminants. These environmental requirements have a direct impact on P/C CLLS system requirements. Data from both ground-based tests and prior missions are available and can be used to develop the environmental aspects of baseline and mission-specific system requirements.

Each of the proposed specific mission scenarios to be evaluated by OEXP directly impacts P/C CLLS system requirements. From a design standpoint, the factors that influence system requirements most significantly include mission duration, crew numbers, resupply capabilities, power availability, accessibility of in-situ resources, radiation flux, gravity, spacecraft design and capabilities and crew labor availability for operation and maintenance. These various factors must be quantified for each proposed mission scenario and subsequently organized to form a consistent set of P/C CLLS system requirements. Data from ground-based tests and prior missions can be used as a starting point for this effort.

The System Requirements element is based on a Work Breakdown Structure that consists of the following sub-elements:

1.4.1.1 Baseline Systems
1.4.1.2 Lunar Base
1.4.1.3 Mars Sprint
1.4.1.4 Mars Base

Development of the baseline system requirements will occur in FY89 and FY90. Work on defining system requirements for specific long-range missions will begin in late FY90 and continue on through FY93.

2.6.1.3 Description

BASELINE SYSTEMS (WBS 1.4.1.1)

A database of human physical, metabolic, and physiological characteristics will be assembled and used to generate a crew PDB. This crew PDB will be used to define the baseline requirements that are to be met by a P/C CLLS system. Baseline parameters for the crew's environment will be defined and documented. Where possible, baseline ranges will be established for allowed P/C CLLS system mass, volume, power consumption, inherent reliability/availability and labor requirements.

The primary deliverables from this sub-element will be the PDB and the baseline requirements for a P/C CLLS system. Both the PDB and the baseline requirements will be transferred to the main P/C CLLS database. The establishment of this main P/C CLLS database is described in the System Analysis and Assessment Element (WBS 1.4.3).

LUNAR BASE (WBS 1.4.1.2)

Work for this sub-element will consist of modifying the baseline crew PDB to incorporate those requirements that are specific to a mission for establishing a lunar base. The baseline parameters relating to the crew's environment will be modified as necessary for this mission. Specific design-related factors for a P/C CLLS will be defined and quantified (i.e. mass, volume, power consumption, etc.). The deliverable from this sub-element will be a set of consistent P/C CLLS system requirements that are specific to this mission. These system requirements will be transferred to the main P/C CLLS data base for access and use during the design and development work. Periodic upgrading of these system requirements may be necessary as the criteria for a lunar base mission evolve with time.

MARS SPRINT (WBS 1.4.1.3)

Work for this sub-element will be analogous to that for the Lunar Base sub-element. In this case, the crew PDB will be modified to reflect the requirements of a Mars sprint mission. The primary deliverable will be a set of consistent P/C CLLS system requirements for this specific mission. Periodic upgrading may also be necessary in this case.

MARS BASE (WBS 1.4.1.4)

Work for this sub-element will be analogous to that for the Lunar Base and Mars Sprint sub-elements. The specific mission will be that of establishing a Mars base.

2.6.1.4 Schedule

Figure 2.6.1-1 is an activity schedule for the System Requirements element that begins with FY89 and extends through FY98. The foregoing descriptions of work for each sub-element of the Work Breakdown Structure cover only the projected activities through the end of FY93. As shown in the figure, it is anticipated that upgrading of the mission-specific P/C CLLS system requirements will continue beyond FY93.

2.6.1.5 Milestones and Deliverables

Figure 2.6.1-2 lists the major milestones and deliverables for the sub-elements in the System Requirements element. Of these, the most important milestones are the definition of the baseline system requirements by the end of FY90 and the establishment of interim mission-specific system requirements by the fourth quarter of FY92. The interim system requirements must be in-place prior to completion of the design package deliverables for each P/C CLLS subsystem. Completion of these design packages is scheduled for the fourth quarter of FY93. As shown in Figure 2.6.1-1, the interim system requirements are expected to undergo further upgrading in the post-FY93 period.

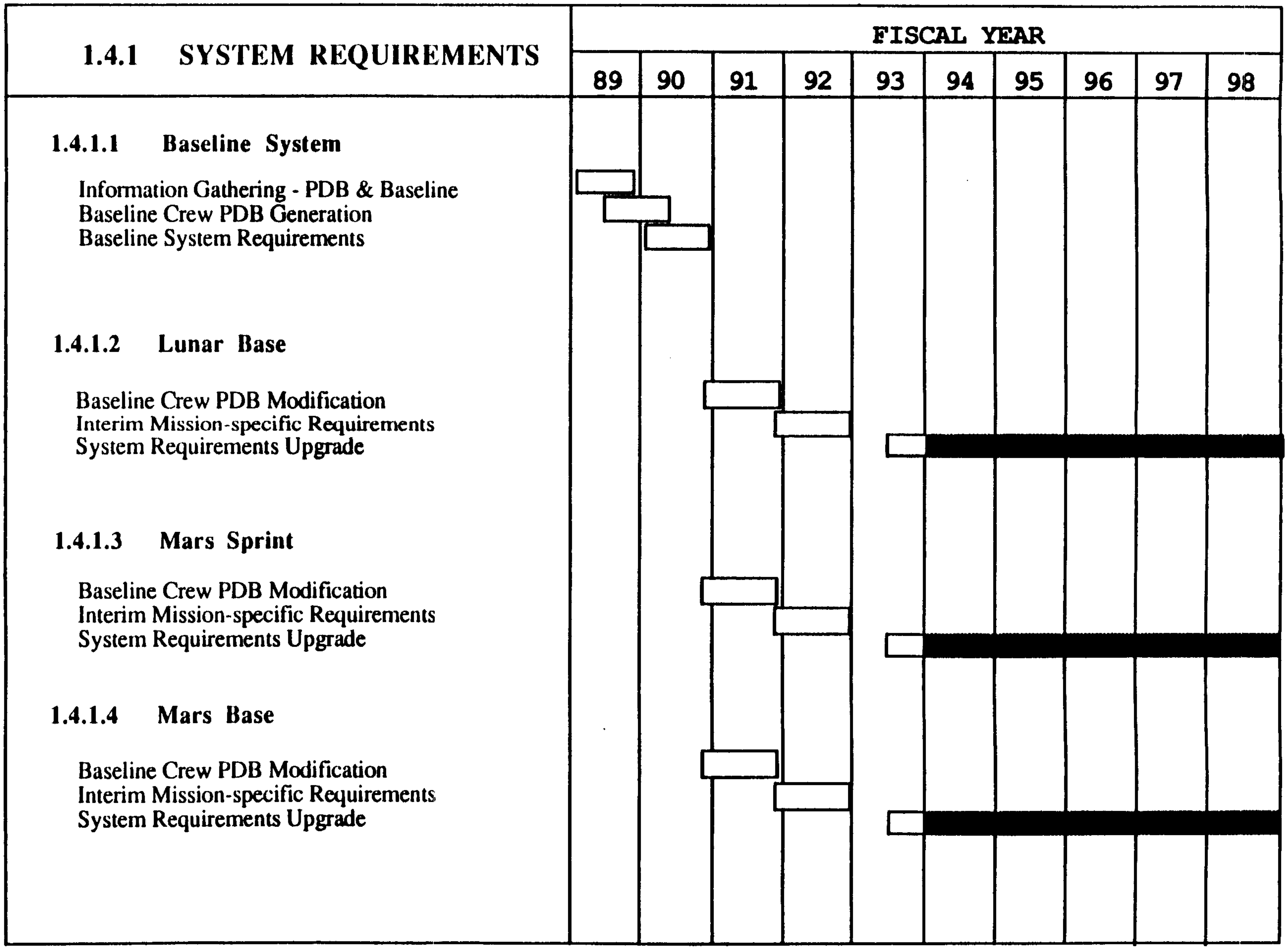

1.4.1 SYSTEM REQUIREMENTS
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.4.1.1 Baseline System
Information Gathering - PDB & Baseline
Baseline Crew PDB Generation
Baseline System Requirements
1.4.1.2 Lunar Base
Baseline Crew PDB Modification
Interim Mission-specific Requirements
System Requirements Upgrade
1.4.1.3 Mars Sprint
Baseline Crew PDB Modification
Interim Mission-specific Requirements
System Requirements Upgrade
1.4.1.4 Mars Base
Baseline Crew PDB Modification
Interim Mission-specific Requirements
System Requirements Upgrade

Figure 2.6.1-1

Figure 2.6.1-2
System Requirements
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.4.1.1 BASELINE SYSTEMS					
• PDB information collected	Δ				
• Crew PDB generated		Δ			
• Baseline Requirements Complete		Δ			
1.4.1.2 LUNAR BASE					
• Baseline PDB modified			Δ		
• Interim System Requirements				Δ	
1.4.1.3 MARS SPRINT					
• Baseline PDB modified			Δ		
• Interim System Requirements				Δ	
1.4.1.4 MARS BASE					
• Baseline PDB modified			Δ		
• Interim System Requirements				Δ	

2.6.2 P/C Bio Systems

2.6.2.1 Objectives

The P/C Bio Systems element is concerned with the integration of P/C technologies and biological processes to form an optimized P/C biological life support system. Specific objectives of this element are as follows:

a. Identify the conditions under which an integrated P/C biological life support system has advantages over a P/C CLLS alone.

b. Identify candidate P/C and biological subsystem technologies for the different processes required in an integrated life support system.

c. Identify the extent to which different waste streams must be processed by P/C technologies for recycling to a plant growth chamber.

Detailed process flow diagrams of integrated hybrid P/C biological life support systems will be prepared for different OEXP-supplied mission scenarios, e.g., for various destinations, extents of on-board food production, and P/C biological subsystem assemblies. State-of-the-art simulation software will be used in the development of models for hybrid systems. The flow diagrams will include mass and energy balance data and the extent of loop closure. Potential closure problems will be highlighted and possible solutions developed. The detailed process flow diagrams will define a hybrid life support system and will also be used for the design evaluation, fabrication, assembly, and testing of breadboard prototype integrated systems or subsystems when appropriate. The knowledge derived from developing and analyzing the flow diagrams will serve as the basis for making decisions concerning how the Pathfinder Program may wish to proceed with hybrid systems beyond FY93.

In developing models of hybrid systems, alternate P/C and biological methods for carrying out specific life support functions will be identified. Data deficiencies will be identified and used as the basis for designing experimental, data gathering protocols.

Designing and developing hybrid systems will also allow the identification of significant interfaces and potential problems associated with those interfaces. Particular attention will be paid to automation and control of integrated hybrid systems during model development.

2.6.2.2 Technical Approach

The subsystems required for recycling in space are generally divided into two categories, P/C and bioregenerative. P/C subsystems rely on combinations of isolated physical and chemical processes to regenerate materials whereas bioregenerative subsystems depend on a number of integrated processes carried out by living organisms. A combination of such processes would result in a hybrid life support system for future long duration missions which may be advantageous for certain mission scenarios. Moreover, certain P/C technologies may have advantages in hybrid systems. For example, wet oxidation, a moderate temperature (150-350 ^{o}C) and high pressure (7-20 MN/m^2) P/C waste treatment process, has several reported advantages over biological methods for processing wastes in space. Some of these advantages are:

- the reactor outflow is sterile
- contaminants, such as volatiles and particulates in air, can be oxidized simultaneously with solid waste slurries
- if high concentrations of organic matter are oxidized, the heat release is rapid and sufficient to maintain the process without an external energy supply
- the process is rapid, complete, and space efficient

On the other hand, biological oxidation processes for waste treatment, such as aerobic digestion, are also reported to have certain advantages for waste treatment. Some of these advantages are:

- organic nitrogen can be easily converted to a desired plant nutrient, NO_3
- the process occurs near ambient temperature
- the outputs will probably be biologically compatible with food production by plants

While physical/chemical methods appear more efficient and reliable than biological methods for treatment of some wastes, the quality of the output streams may not lead to complete loop closure for some materials. Each recycling method must therefore be explored with parametric analysis and experimental programs to evaluate their compatibility with a given integrated system concept. From such studies an optimized design for an integrated P/C biological system can be derived.

Although the above is only one example in which either a P/C or biological subsystem may be used to carry out a process in an integrated life support system, there are other examples (e.g. air revitalization and potable water reclamation) that are also worthy of consideration. It is one of the purposes of this element to identify and assess the advantages of alternate processing schemes.

The approach to achieving the objectives of the P/C Bio Systems element will be based on a Work Breakdown Structure that consists of the following three sub-elements:

1.4.2.1 Concepts/Integration Analysis
1.4.2.2 Integration Requirements
1.4.2.3 Control

The combination of work to be done in these three sub-elements will lead to designs for hybrid integrated life support system designs which have been optimized through inclusion of both P/C and biological subsystems. It is expected that these designs will allow decisions to be made for further hardware development and testing.

The Concepts/Integration Analysis sub-element will focus on the development of concepts for integrating P/C and biological life support subsystems, including evaluating and selecting subsystems and then integrating the functional subsystems into a hybrid life support system. Analysis of integrated systems concepts will be done by computer modeling and simulation studies. Models will be developed for the following mission scenarios:

- A generic mission
- Missions with increasing amounts (3-97%) of food produced in space
- Lunar base missions
- Missions to Mars

Emphasis will be placed on maximizing the degree of closure of the life support system. Finally, efforts will be devoted to developing a generic model which is not mission-specific.

A knowledge of integration requirements for a hybrid system containing both P/C and biological subsystems will provide inputs for the Concepts/Integration Analysis sub-element. The work for the Integration Requirements sub-element will provide these inputs by gathering and organizing results of studies conducted under the Plant Interface sub-elements of the Air Revitalization (WBS 1.1.2), Water Management (WBS 1.1.3) and Solid Waste Management (WBS 1.1.4) elements. The development of the desired integration requirements will also draw on the work conducted for the System Requirements (WBS 1.4.1) element.

Both control strategies for automation and instrumentation for control and monitoring must be considered during integration analysis and the development of models for subsystems and integrated systems. Control of biological subsystems is more complex than for P/C systems, and selection of a hybrid system will be based in part on considerations of the complexity of control of the hybrid system. However, it is anticipated that major consideration of control problems will occur after acceptable models for integrated hybrid systems have been derived. Therefore, work devoted solely to control questions will become more important after subsystems for integration have been selected and preliminary integration studies have been performed by computer modeling and simulation methods.

The work to be performed for the Control sub-element will concentrate on developing specifications of the instrumentation and automated control requirements for the mission scenarios considered under the Concepts/Integration Analysis sub-element. During this work, an effort will be made to keep abreast of the results developed under the Systems Control and Monitoring Instrumentation (WBS 1.3.1) and Systems Control Strategy (WBS 1.3.2) elements.

The approach to achieving optimized designs will rely on modeling (using process simulation software) and laboratory experiments. Modeling will be used to perform trade-off studies of different design concepts in order to arrive at optimized designs based on weight, volume, power, and thermal needs considerations. In order to develop realistic models of integrated P/C biological life support systems, an experimental program must be conducted in parallel with the modeling effort. Experiments will clarify the characteristics of the interface between the P/C and the biological subsystems, and provide data that is currently unavailable but essential for model development. For example, to aid in developing realistic process flow diagrams, laboratory experiments will be performed to determine the extent to which wastes from different sources must be processed by P/C methods before recycling to a plant growth chamber of a biological sub-system.

2.6.2.3 Description

As crews get larger and distances from Earth greater, more reliance will fall on bioregenerative systems to meet human requirements for water, food, and oxygen. An evaluation of the consequences of such an evolution is essential. It is the primary purpose of the P/C Bio Systems element to perform this evaluation.

CONCEPTS/INTEGRATION ANALYSIS (WBS 1.4.2.1)

The work for this sub-element will utilize computer modeling to aid in the selection of the subsystems for a hybrid life support system. Initially the work will emphasize the definition of concepts and their incorporation in the design of integrated systems.

Conceptual designs will be developed for integrated P/C and biological life support systems containing, for example, a plant growth chamber and an unconventional food generation system. An assumption that might be used in developing such a design is that bioproduction of crew food will range from 3 to 97% with the remainder of the food requirement derived from stores. The impact of such a reliance on onboard food production upon oxygen generation, potable water production, and carbon dioxide removal will be assessed. Energy and material balances will be derived for several different scenarios in which P/C bioregenerative subsystems are integrated into a life support system. Potential closure problems will be identified and alternate solutions will be developed. Emphasis will be placed on achieving a high degree or extent of recycling. Commercial simulation software will be used to evaluate the different concepts. Custom code will be written when needed to accommodate subsystems of interest.

In order to meet the objectives of the P/C Bio Systems element, laboratory experiments will be performed to determine the extent to which waste processing is necessary before transferring materials to a plant growth chamber. Emphasis will be placed on minimizing the extent of processing required for urine, feces, biomass, food preparation waste and water from evapotranspiration of plants. The information derived from these experiments will be used in the modeling work for integration analysis.

It is anticipated that the hybrid P/C Bio life support systems will become more attractive for longer duration stays in space, such as Mars missions or lunar base applications. Therefore, requirements and in-situ resources for these missions will be taken into account in developing conceptual designs of hybrid life support systems. Simulation modeling of the conceptual designs will include preliminary evaluations of these factors.

The integration analysis work will concentrate on refining and utilizing computer models of hybrid integrated systems for Mars and lunar missions. The advantages and disadvantages of hybrid systems over P/C systems alone for Mars and lunar missions will be studied. Commercial state-of-the-art software will used for model development and analysis. Flow diagrams of integrated hybrid systems showing mass and energy balance and degree of closure will be developed. Assumptions used in model development will be clearly described.

Integration analysis work will also include modeling studies in which the amount of onboard food production is increased from 3 to 97% for Mars and lunar missions. The hybrid systems with increasing food production will be compared with a P/C integrated system and the comparative advantages of each integrated system will be identified. It is anticipated that some of these studies will be performed at a supporting center such as JPL.

The determination of waste processing minimums will be pursued as part of the work for the Concepts/Integration Analysis sub-elements. This work will consist of an experimental program having as its primary objective a determination of the minimum amount of waste (urine, feces, inedible biomass, food preparation waste, and evapotranspiration water) processing that will be required by P/C methods before returning the products to a plant growth chamber. The results derived from the experimental program will be used to prepare more realistic waste processing scenarios during development of integrated hybrid P/C biological life support system models and designs.

The primary deliverable from the Concepts/Integration Analysis sub-element will be a set of recommendations that address the objectives of the P/C Bio Systems element. These recommendations will also define required follow-on work that will lead to functioning P/C biological life support systems.

INTEGRATION REQUIREMENTS (WBS 1.4.2.2)

Preliminary integration requirements for hybrid P/C biological life support systems will be developed in FY89 to allow the conceptual design studies to proceed. Interim definitions of mission-oriented requirements will be prepared over the course of FY90 and FY92. The preparation of these interim definitions will follow from work performed for the System Requirements element (WBS 1.4.1).

CONTROL (WBS 1.4.2.3)

Preliminary requirements for automated control strategies and the accompanying sensors and instrumentation will be defined during the various aspects of the integration analysis work. These preliminary requirements will evolve into more detailed requirements as results are generated from the various studies

2.6.2.4 Schedule

Figure 2.6.2-1 is an activity schedule for the P/C Bio Systems element that begins in FY89 and continues through FY98. The foregoing descriptions of work under each sub-element of the Work Breakdown Structure cover the activities through the end of FY93. As indicated by the solid lines, some follow-on work will continue after FY93.

2.6.2.5 Milestones and Deliverables

Figure 2.6.2-2 lists the major milestones and deliverables for the P/C Bio Systems element. Owing to the highly research-oriented nature of the work, these milestones are quite general. The major deliverable will be the recommendations issued at the end of FY93.

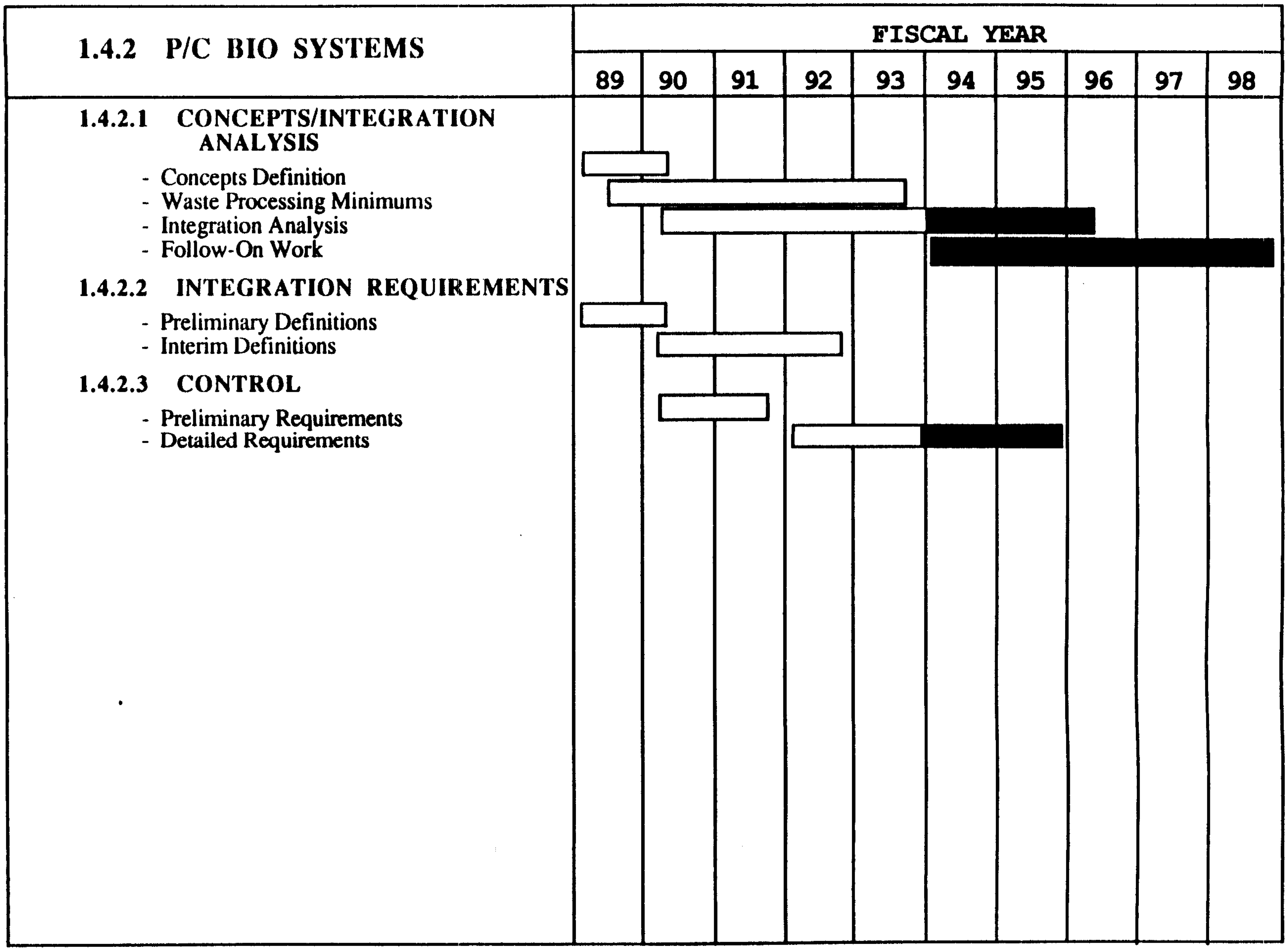

1.4.2 P/C BIO SYSTEMS
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.4.2.1 CONCEPTS/INTEGRATION ANALYSIS
- Concepts Definition
- Waste Processing Minimums
- Integration Analysis
- Follow-On Work
1.4.2.2 INTEGRATION REQUIREMENTS
- Preliminary Definitions
- Interim Definitions
1.4.2.3 CONTROL
- Preliminary Requirements
- Detailed Requirements

Figure 2.6.2-1

Figure 2.6.2-2

P/C Bio Systems
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.4.2.1 CONCEPTS/INTEGRATION ANALYSIS					
• Concepts Defined		Δ			
• Processing Minimums Defined					Δ
• Integration Analysis Complete					Δ
• Recommendations Complete					Δ
1.4.2.2 INTEGRATION REQUIREMENTS					
• Preliminary Requirements Defined		Δ			
• Interim Requirements Defined				Δ	
1.4.2.3 CONTROL					
• Preliminary Requirements Defined			Δ		
• Detailed Requirements Defined					Δ

2.6.3 System Analysis and Assessment

2.6.3.1 Objectives

During the first five years of the project, the primary objectives of the System Analysis and Assessment element will be the pursuit of leadership and guidance-related activities that will insure the timely development of the required mission-specific, optimized P/C CLLS systems. In particular, these activities will be designed to achieve the following secondary objectives:

a. Establish the current state of the art in P/C life support subsystem technology.

b. Analyze and refine existing systems assessment procedures to allow consideration of the whole spacecraft or base and to permit evaluation of a wide range of P/C CLLS system designs.

c. Establish interface requirements, design guidelines, and optimal configurations for meeting specific mission requirements.

d. Identify the P/C technologies critical to achieving a reliable, efficient and economical mission-specific, integrated systems.

Long-duration space missions planned for the early 21st century must provide life support functions for a wide range of scenarios. Procedures must be developed that will systematically define the life support system requirements for each of the missions and quantitatively analyze and compare the various system/subsystem technology options to achieve the life support function in a reliable, efficient and economical manner. The results of these analyses and comparisons must then be communicated to the various participating NASA centers that have lead responsibility for developing optimized designs for the individual subsystems.

A broad-based system-level model will be formulated that represents the interaction of the various life support subsystems with the crew, other vehicle systems, and the cabin environment. This model will provide a useful tool for identifying technologies with the highest system payoff potential, assuring that technologies and subsystems will function in an integrated manner, and assisting in the development of design guidelines and interface requirements.

Modeling-intensive Subsystem and System Analysis sub-elements are present in the WBS for the technical elements that deal with Thermal Control (WBS 1.1.1), Air Revitalization (WBS 1.1.2), Water Management (WBS 1.1.3) and Solid Waste Management (WBS 1.1.4). It is important that these simulation modeling efforts be conducted with a full awareness of the mission-specific system-level requirements that must be satisfied by a particular subsystem. For this reason, the modeling work for the particular P/C subsystems must be performed from an integrated system viewpoint, especially in the area of supporting the preparation of design packages. However, it is also important that these system-level analyses be developed through guided modifications and refinements of the subsystem models themselves.

The broad-based system-level model to be formulated for the System Analysis and Assessment element will be used for top-level payoff/trade-off and optimization studies. System-level logistic analysis and peformmace predictions will also be developed. The results of these studies will be communicated to the appropriate participating NASA centers to provide guidance for the ongoing work. It is anticipated that all of the participating NASA centers will provide input on the design of this system-level model.

2.6.3.2 Technical Approach

Mission and spacecraft criteria impose major constraints on the life support subsystems. The mission duration and degree of closure of life support system have pronounced effects on system weight, volume, electrical power, and heating and cooling requiremnts. A critical examination of the current state-of-the art reveals that system integration problems are poortly understood and no serious effort is underway to systematically assess the payoffs or requirements of alternative system elements. The interplay of subsystem elements for controlling the cabin environment, managing water, waste, and food needs, providing for the monitoring and control of functions, and interfacing with crew and the vehicle must be addressed in a systematic manner. Without such a systems approach, it is highly improbable that life support research and development will take on meaningful directions for the fulfillment of proposed missions.

The approach to achieving the objectives of the System Analysis and Assessment element will be based on a Work Breakdown Structure that contains the following seven sub-elements:

1.4.3.1 Analytical Techniques
1.4.3.2 Technology Assessment
1.4.3.3 Payoff/Trade-off Assessment
1.4.3.4 Optimization Studies
1.4.3.5 Logistic Analysis
1.4.3.6 Performance Predictions
1.4.3.7 Information Transfer

The Analytical Techniques sub-element will focus initially on surveying the software to be used for modeling work under each of the P/C elements. The intent of this survey will be that of gaining an awareness of the modeling techniques which will be used early in the project. Work for this element will continue in an overview fashion throughout the project and will evolve into the role of remaining cognizant of the types of models which are in use for the individual technical elements.

The Technology Assessment sub-element will be emphasized strongly in the first year of the P/C CLLS project. Studies will be performed with the intent of defining the readiness status of subsystem technologies. Emphasis will be placed on those technologies which might be employed in the Air Revitalization and Water Management subsystems.

The Payoff/Trade-off Assessment sub-element will be concerned initially with the development and implementation of the broad-based, system-level model. After implementation, initial uses of the model will be those of performing payoff and trade-off assessments on the use of differing technologies in the various P/C CLLS subsystems. These studies will provide guidance for the development of mission-specific subsystem designs by the P/C technical elements.

The sub-elements dealing with Optimization Studies, Logistics Analysis and Performance Predictions will include a range of modeling studies that will support the design of the integrated, mission-specific P/C CLLS systems. It is anticipated that these studies will be phased-in when the work on the development and design of the various subsystems reaches an advanced stage.

The Information Transfer sub-element will take an overview approach to the question of transferring payoff/trade-off and other system-level study results to the participating NASA centers. This sub-element will also serve as the focal point for other information-transfer-related issues such the design of the P/C CLLS database and the protocol for archiving models of the individual subsystems.

2.6.3.3 Description

ANALYTICAL TECHNIQUES (WBS 1.4.3.1)

All of the P/C technical elements will begin to employ simulation models for technology and design evaluations at an early stage of the project. The modeling plans at each lead center will be surveyed to gain an awareness of the techniques and software to be used in the work. Inputs will also be gathered from other life support research-related modeling work at ARC and other centers. An informational assessment of available modeling software and techniques will be prepared and distributed to all participating centers.

An awareness of the current state of simulation modeling will be maintained throughout the course of the five years covered by this project plan. The informational assessment of software and techniques will be updated and distributed as appropriate. The intent of this effort will be that of keeping the participating centers abreast of the latest developments in this area.

TECHNOLOGY ASSESSMENT (WBS 1.4.3.2)

The work to be done for this sub-element will consist of preparing assessments of the state of development and readiness of those technologies which could be considered as prime candidates for use in subsystem designs. In view of the critical importance of water reclamation for long-duration missions, the initial technology assessments in FY89 will focus on candidates for this subsystem. If resources and staffing permit, a similar technology assessment will be performed for Air Revitalization candidates.

Current plans envision performing the desired technology assessments in FY89 with completion in early FY90 (at the latest). This timing is required to make the results available to the corresponding technical element at an early stage in the work. However, it is possible that the work itself will reveal a need for further technology assessments in subsequent years. These additional assessments will be incorporated in revisions of this project plan when appropriate.

PAYOFF/TRADE-OFF ASSESSMENT (WBS 1.4.3.3)

The goal in performing the work for the Payoff/Trade-off Assessment sub-element is to maintain a mission-driven systems view of the integrated P/C CLLS system and continually assess its performance capability in light of a given mission's objective. The initial step will be devoted to establishing a current state-of-the-art baseline for the P/C CLLS system. The output of this initial effort will be to quantitatively define the baseline state-of-the-art system and the functional requirements and operational constraints for each proposed mission in the form of modified versions of the baseline system.

The findings gathered under the Analytical Techniques sub-element will be used to make decisions on the software and simulation modeling techniques to be used for developing the broad-based system-level model. Inputs from all participating centers will be sought in this area. Once decisions have been made with respect to software and technique, the system-level model will be coded, debugged and brought to a working level state of readiness. An attempt will be made to reach this stage in the work by early FY91.

Payoff/trade-off assessment methodology will also be developed. The methodology will adequately represent the performance of each subsystem in terms of weight, volume, and power requirements as well as scaling laws and parametric data so subsystems can be examined for meeting varying mission requirements. The interactions and interrelationships between the mission environment, the spacecraft structure and systems, and the life support subsystems will be incorporated into the system-level analytical procedure. Optimization techniques will be incorporated into the model to identify parameters that minimize overall life-support weight, volume, power or cost estimates. Much of this work on methdology will proceed in conjunction with designing and coding the system-level model itself.

A series of in-depth system payoff/trade-off analyses will be performed to establish which subsystems or combinations of subsystems warrant further development for the specific mission applications. These analyses will examine advanced technology identified by previous assessments. Subsystem interface issues and concerns will be identified so that further technology development may proceed in the direction of minimizing these issues. Continual support will be provided to the technical elements by quantifying the effect of alternative design decisions on total system performance and capability.

The work to perform these system payoff/trade-of analyses will begin in FY91 and receive strong emphasis over the course of the year.

OPTIMIZATION STUDIES (WBS 1.4.3.4)

This work will proceed from an integrated P/C CLLS systems viewpoint and will insure that optimization decisions made at the subsystem level are consistent with mission constraints. The results of these studies with the system-level model will be continually fed back to the appropriate technical element. This work will be performed in FY91 and FY92.

LOGISTICS ANALYSIS (WBS 1.4.3.5)

The future long-duration space missions will require much greater autonomy from ground-based support and logistics systems than before. These missions will require life support systems that are extremely reliable and that can be maintained during the mission. The Logistics Analysis sub-element will address the reliability/maintainability issues and how they can be effectively managed by the crew and resources aboard the spacecraft or at the base. Crew systems interface requirements and design guidelines will be established to provide safe, effective operational procedures in both normal and emergency situations.

The work to establish these guidelines will draw on the results of the System Requirements element (WBS 1.4.1.).

PERFORMANCE PREDICTIONS (WBS 1.4.3.6)

This work will receive emphasis in FY92 and FY93 and will serve to support the preparation of the design package deliverables for the individual P/C technical elements. Continued refinement of the system-level model will allow its use for performance predictions in support of follow-on testing. For this reason, work in this sub-element is expected to continue beyond FY93.

INFORMATION TRANSFER (WBS 1.4.3.7)

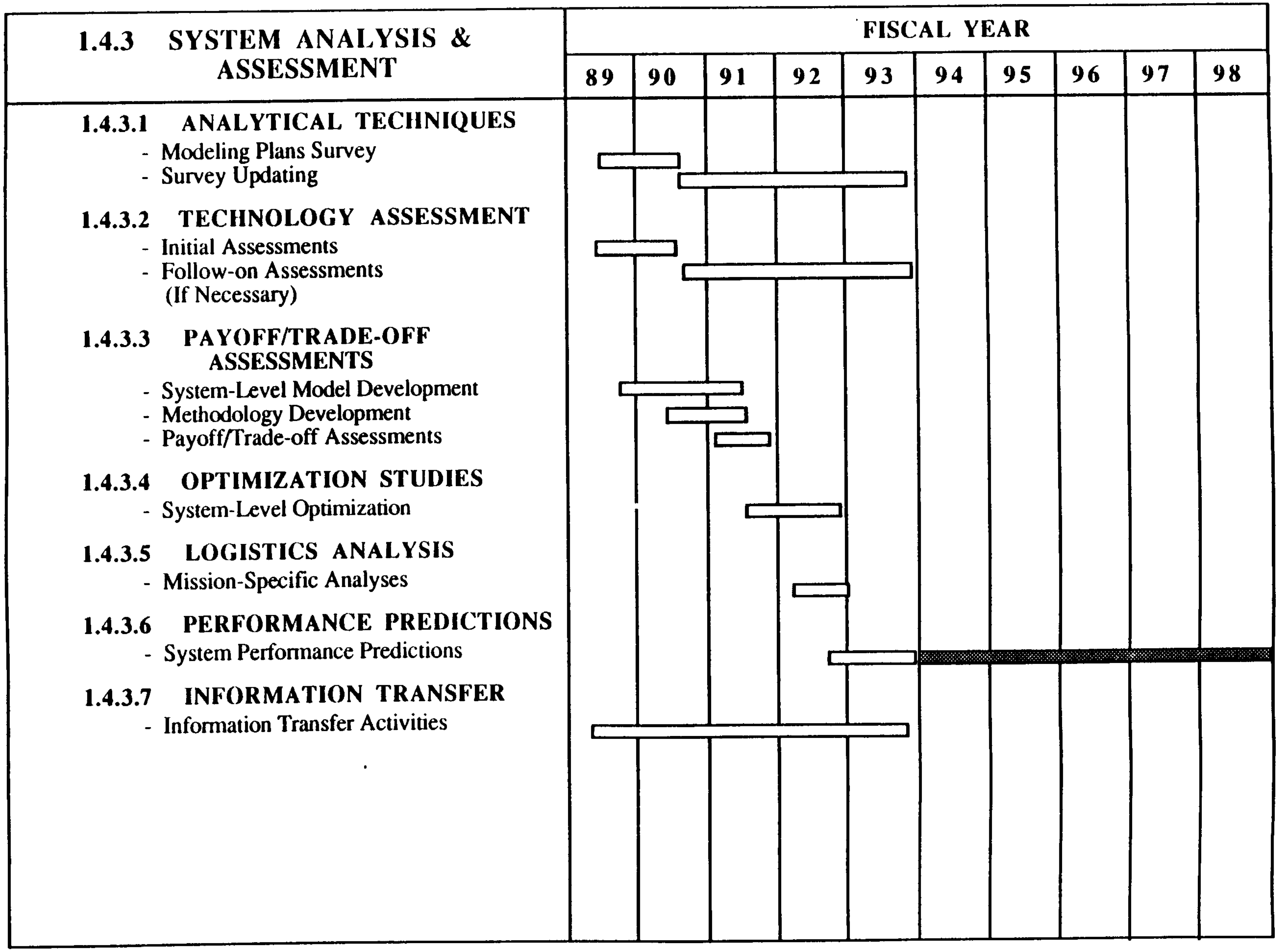
Work for this sub-element will consist of a single omnibus tasks that is designed to speed the transfer of system analysis and assessment results to the appropriate participating NASA centers. This sub-element will also serve as the focal point for documenting and disseminating the decisions of the Intercenter Working Group on information transfer issues. Examples of these issues include the format and content of the design packages, the design of the P/C CLLS database and the protocol and methodology for archiving subsystem models.

2.6.3.4 Schedule

See Figure 2.6.3-1.

2.6.3.5 Milestones/Deliverables

See Figure 2.6.3-2.



1.4.3 SYSTEM ANALYSIS & ASSESSMENT
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.4.3.1 ANALYTICAL TECHNIQUES
- Modeling Plans Survey
- Survey Updating
1.4.3.2 TECHNOLOGY ASSESSMENT
- Initial Assessments
- Follow-on Assessments (If Necessary)
1.4.3.3 PAYOFF/TRADE-OFF ASSESSMENTS
- System-Level Model Development
- Methodology Development
- Payoff/Trade-off Assessments
1.4.3.4 OPTIMIZATION STUDIES
- System-Level Optimization
1.4.3.5 LOGISTICS ANALYSIS
- Mission-Specific Analyses
1.4.3.6 PERFORMANCE PREDICTIONS
- System Performance Predictions
1.4.3.7 INFORMATION TRANSFER
- Information Transfer Activities

Figure 2.6.3-1

Figure 2.6.3-2

System Analysis and Assessment
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.4.3.1 ANALYTICAL TECHNIQUES					
• Initial Survey Complete		Δ			
• Updates Complete			Δ	Δ	Δ
1.4.3.2 TECHNOLOGY ASSESSMENT					
• Initial Water Reclaiming Technology Assessment Complete		Δ			
• Initial Air Revitalization Technology Assessment Complete (If pursued)		Δ			
1.4.3.3 PAYOFF/TRADE-OFF ASSESSMENTS					
• System-level Model Complete			Δ		
• Analytical Methodology Complete			Δ		
• Assessments Complete			Δ		
1.4.3.4 OPTIMIZATION STUDIES					
• System-level Studies Complete				Δ	
1.4.3.5 LOGISTICS ANALYSIS					
• Mission-specific Analyses completed				Δ	
1.4.3.6 PERFORMANCE PREDICTIONS					
• System-level Predictions Completed					Δ
1.4.3.7 INFORMATION TRANSFER		(no specific Milestones)			

2.6.4 Validation and Verification

2.6.4.1 Objectives

The primary objective of this element is to develop a general strategy for validating the predictions of the computer simulation models that will be used to develop each mission-specific design of the individual P/C CLSS subsystems. In the near term, this general validation strategy will be applied to the simulation models that are employed during the course of the design of each mission-specific subsystem. From the long-term standpoint, the validation strategy will be sufficiently flexible to readily accommodate changes that become necessary as each subsystem design and its associated simulation model move through the stages of breadboard prototype, integrated test bed and flight hardware.

A second objective of this element will be the complementary development of test inputs and resulting outputs to be used for checking and verifying the continuing integrity of the computations performed by the various models. These test inputs will be employed after the implementation of all coding changes to catch inadvertent errors and avoid the generation of misleading results.

2.6.4.2 Technical Approach

The computer simulation model of each mission-specific subsystem design will serve the entire range of development stages including the final fabrication of the mission hardware itself. It is expected that some modification and upgrading of the individual models will be required to meet the specific needs of each stage of development. The application of pertinent validation and verification checks will be a necessary part of the effort to modify and upgrade each mission-specific model. In turn, the validation and verification checks themselves will be refined as required to be consistent with the goals of the development effort.

The approach to achieving the objectives of the Validation and Verification element will be based on a Work Breakdown Structure that consists of the following two sub-elements:

1.4.4.1 Ground Test Data

1.4.4.2 Flight Test Data

The Ground Test Data sub-element will cover the majority of the work for the Validation and Verification element. The effort will begin in FY89 with an initial definition of a general strategy for validating the predictions of the various subsystem simulation models. This general validation strategy will be designed to be applicable to the simulation models used in the Subsystem and System Analysis sub-elements for the elements that deal with Thermal Control (WBS 1.1.1), Air Revitalization (WBS 1.1.2), Water Management (WBS 1.1.3), Solid Waste Management (WBS 1.1.4), and Food Management (WBS 1.1.5).

The general validation strategy will be reviewed annually and tested through application in FY90 through FY93. The validation data for each mission-specific subsystem simulation model will be gathered as part of the work for the Subsystem Tests sub-element in the Work Breakdown Structure for each of the above-listed P/C Life Support elements (WBS 1.1). Annual revisions in the validation strategy will be based on perceived needs and problems encountered in the initial applications.

Work for the Ground Test Data sub-element will also cover the development of initial test inputs and resulting outputs for checking the computational integrity of the mission-specific simulation models. This work will occur in the FY91 to FY93 time frame in a manner to be determined by the rate of progress on modeling within each P/C subsystem area. Final verifications of the computational integrity of each subsystem design model will be performed once the validation process is complete.

The Ground Test Data sub-element of the Validation and Verification element will be extended into the post-FY93 time frame. The work will consist of modifying the validation strategy and the inputs for verification of computational integrity as necessary to meet the needs of the successive stages of development. These development stages will include breadboard prototypes, integrated P/C system test beds and human-rated, full-scale ground tests. All of the necessary data for the validation checks themselves will be derived from the ongoing results of the development tests.

All of the work for the Flight Test Data sub-element will be performed in the post-FY98 time frame. In the case of this sub-element, the development stages will probably be Shuttle-based flight tests and space-based test beds.

2.6.4.3 Description

The following is a description of the work to be done in the sub-elements of the Work Breakdown Structure for the Validation and Verification element:

GROUND TEST DATA (WBS 1.4.4.1)

a. Definition of Initial Validation Strategy

A paper study will be performed to prepare an initial strategy for validation of the predictions of the computer simulation models of the various subsystems. This work will consist of brief reviews of the technologies used in each P/C subsystem. The intent of these reviews will be a determination of those process variables that can be easily measured in experimental tests with partial subsystems and which will also best characterize the subsystem performance. The results of these reviews will be combined with assessments of the software packages used in the modeling work and decisions will be made to define the initial validation strategy in general terms. The work to define the initial validation strategy will be started in FY89 and completed in FY90.

b. Refinement of Validation Strategy

The initial validation strategy will be refined on a year-by-year basis during FY90 through FY93. Inputs to this refinement process will include progress made during work for the Subsystem Analytical Modeling sub-elements and results of initial model validations for the various subsystem designs.

c. Definition of Verification Tests

Sets of verification tests will be defined to test the computational integrity of the various subsystem simulation models. This work will be done in FY91 and FY92 as the individual mission-specific subsystem designs reach the stage where verification tests will be meaningful. The emphasis will be that of defining a set of inputs and resulting outputs that will test for inadvertent errors which may occur after changes are made in the model coding. It is expected that the set of inputs and outputs will be somewhat different for each subsystem simulation model.

d. Refinement of Verification Tests

The verification tests will be further refined in FY93 once the individual subsystem models have been validated. The intent will be that of passing a set of model-specific verification tests for each design to the next stage of development.

The elements associated with refinement of both the validation strategy and the verification tests will carry on in FY94 through FY98 as needed to serve the individual stages of the P/C CLSS development program.

FLIGHT TEST DATA (WBS 1.4.4.2)

All work on this sub-element will occur in the post-FY98 period. Refinements of the validation strategy and verification tests will continue as needed to serve development work based on shuttle flight tests and test beds located in space.

2.6.4.4 Schedule

See Figure 2.6.4-1.

2.6.4.5 Milestones/Deliverables

See Figure 2.6.4-2.

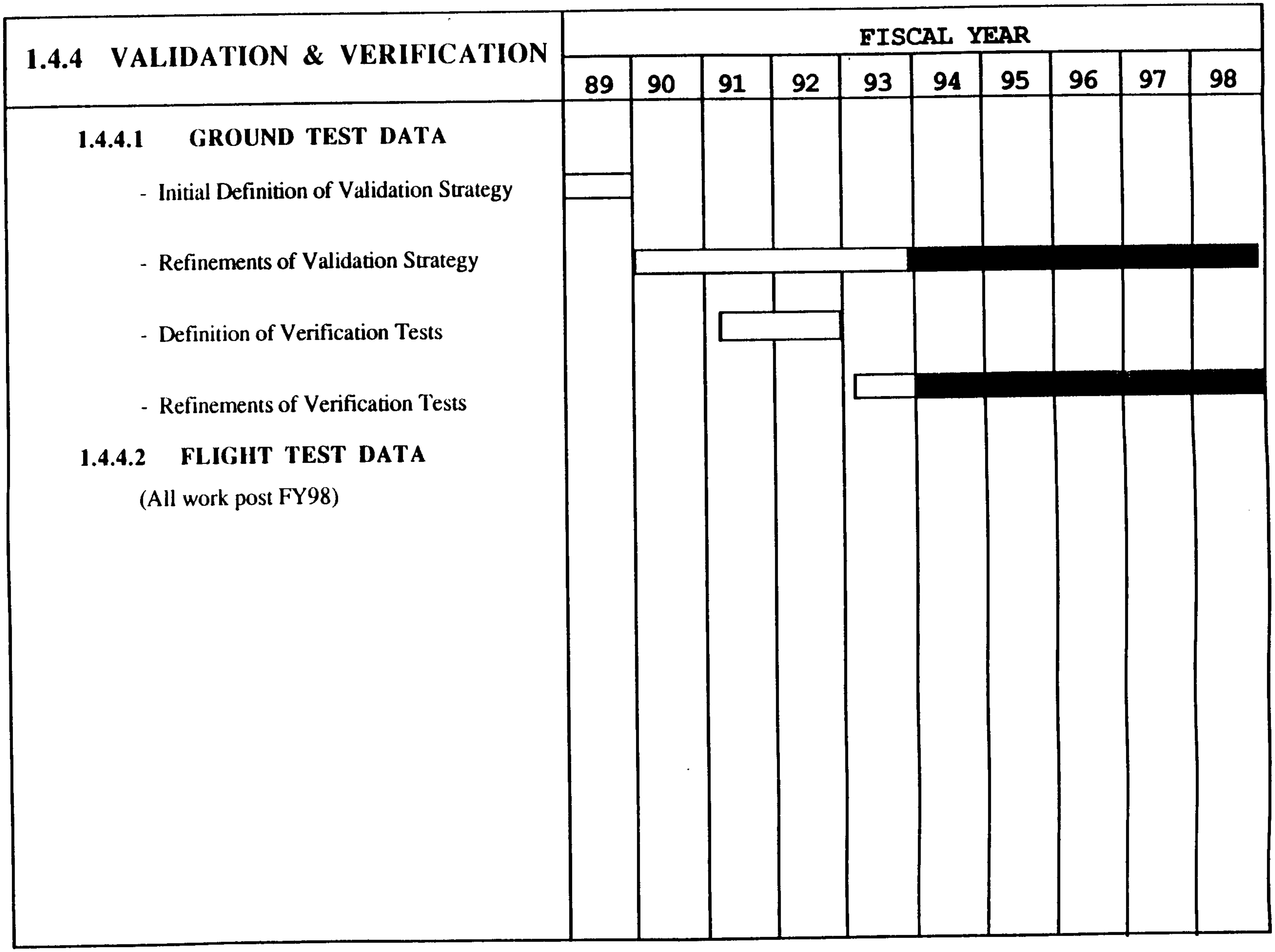

1.4.4 VALIDATION & VERIFICATION
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.4.4.1 GROUND TEST DATA
- Initial Definition of Validation Strategy
- Refinements of Validation Strategy
- Definition of Verification Tests
- Refinements of Verification Tests
1.4.4.2 FLIGHT TEST DATA
(All work post FY98)

Figure 2.6.4-1

Figure 2.6.4.-2
Validation & Verification
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
WBS 1.4.4.1 GROUND TEST DATA					
• Initial strategy defined		Δ			
• Final Strategy refinements					Δ
• Verification tests defined				Δ	
• Verification test refinements					Δ
WBS 1.4.4.2 FLIGHT TEST DATA					
• All work post FY 98					

2.6.5 System Tests

System tests are required to demonstrate that hardware intended for use in space functions according to design and need. Ground-based subsystem tests will be initiated in early FY94, and space-based testing will begin as required in mid-FY99. All levels of hardware development will first be modeled analytically, from process through integration into subsystems and systems. Only when analysis has demonstrated that technologies are critical to a life support system will full-scale hardware development begin. Analysis will, in some cases, require breadboard prototype development and testing to provide data for modeling and to supply feedback to ongoing laboratory-based R & D efforts. Further testing of partial and complete P/C CLLS subsystems may also be required to meet these same needs.

Within the context of this five-year project plan, the Systems Tests elements has been structured to meet the need for testing that is supportive of research and development-oriented laboratory and analytical modeling efforts. This type of testing is not intended to supplant human-rated, full-scale tests of mission-specific P/C CLLS systems. These full-scale tests are covered in the Human-Rated Tests elements (WBS 1.4.6) of this project plan.

2.6.5.1 Objectives

The objectives of the System Tests element are directed primarily toward identifying needed tests and assessing the suitability of existing facilities for conducting these tests. In specific terms, these objectives are as follows:

a) Monitoring the R & D progress in the areas of the primary P/C technical elements and defining the testing requirements and needs that must be met to support these efforts.

b) Reviewing the results of an assessment of existing facilities at the participating NASA centers (See Section 4.0) and determining their suitability for needed tests.

c) Determining the need for, and scope of, flight experiments that are specific to supporting and directing P/C CLLS R & D projects.

2.6.5.2 Technical Approach

The approaches to prototype and subsystem testing on the ground have been developed by NASA over the past 25 years. These approaches have been documented both formally and informally, and will be followed to the degree that is consistent with the goals of the particular tests themselves. Since these tests will be oriented toward the support of laboratory and analytical modeling efforts, some modification of past approaches to hardware testing may be necessary.

Research-oriented tests of breadboard prototypes, partial subsystems and full-scale subsystems require flexible, multi-purpose facilities that are equipped to provide services such as cooling, power, computation, data analysis and physical and chemical analysis. Existing test facilities at the participating NASA centers will be examined as part of the overall facilities assessment to be conducted by P/C CLLS project management in FY89. The results of these examinations must be reviewed in light of identified needs for specific tests. Decisions must then be made with respect to the suitability of these existing facilities for conducting the desired tests.

The objectives of the System Tests element will be met by utilizing a Work Breakdown Structure that contains the following three sub-elements:

1.4.5.1 Requirements
1.4.5.2 Test Facility Reviews
1.4.5.3 Flight Experiments

2.6.5.3 Description

REQUIREMENTS (WBS 1.4.5.1)

The work for this sub-element will be of a monitoring and planning nature. Beginning in FY90, the R & D progress in each of the P/C CLLS technical elements will be monitored with the intent of identifying needs for testing prototypes, partial subsystems and systems to provide essential data for decision-making and/or model validation. The planning aspect will be concerned with defining both the data to be obtained through testing and the equipment that is required for making the necessary measurements.

TEST FACILITY REVIEWS (WBS 1.4.5.2)

Work conducted for this sub-element will consist of reviewing the capabilities of existing test facilities at the participating NASA centers and determining which (if any) of these are suitable for each of the tests defined by the Requirements sub-element. Detailed information on the existing test facilities will be drawn from the assessments to be developed by P/C CLLS project management in FY89.

It is anticipated that this work will begin at a modest level in FY90 and continue through FY93. The tests themselves will be conducted under the Subsystem Test sub-elements for the individual Physical/Chemical Life Support elements (Air Revitalization, Water Management, etc.).

FLIGHT EXPERIMENTS (WBS 1.4.5.3)

The need for research-oriented flight experiments (if any) will be addressed from a planning point-of-view. If such needs are identified, the experiments themselves will not occur during the five years covered by this project plan. Identification of flight experiment needs is targeted for the end of FY93.

2.6.5.4 Schedule

See Figure 2.6.5-1.

2.6.5.5 Milestones/Deliverables

See Figure 2.6.5-2

1.4.5 SYSTEM TESTS

1.4.5.1 REQUIREMENTS

- R & D Monitoring & Identification of Testing Needs

1.4.5.2 TEST FACILITY REVIEWS

- Capabilities Assessments, Existing Test Facilities

1.4.5.3 FLIGHT EXPERIMENTS

- Identification of Needs
- Flight Experiment Development
- Flight Experiments Conducted

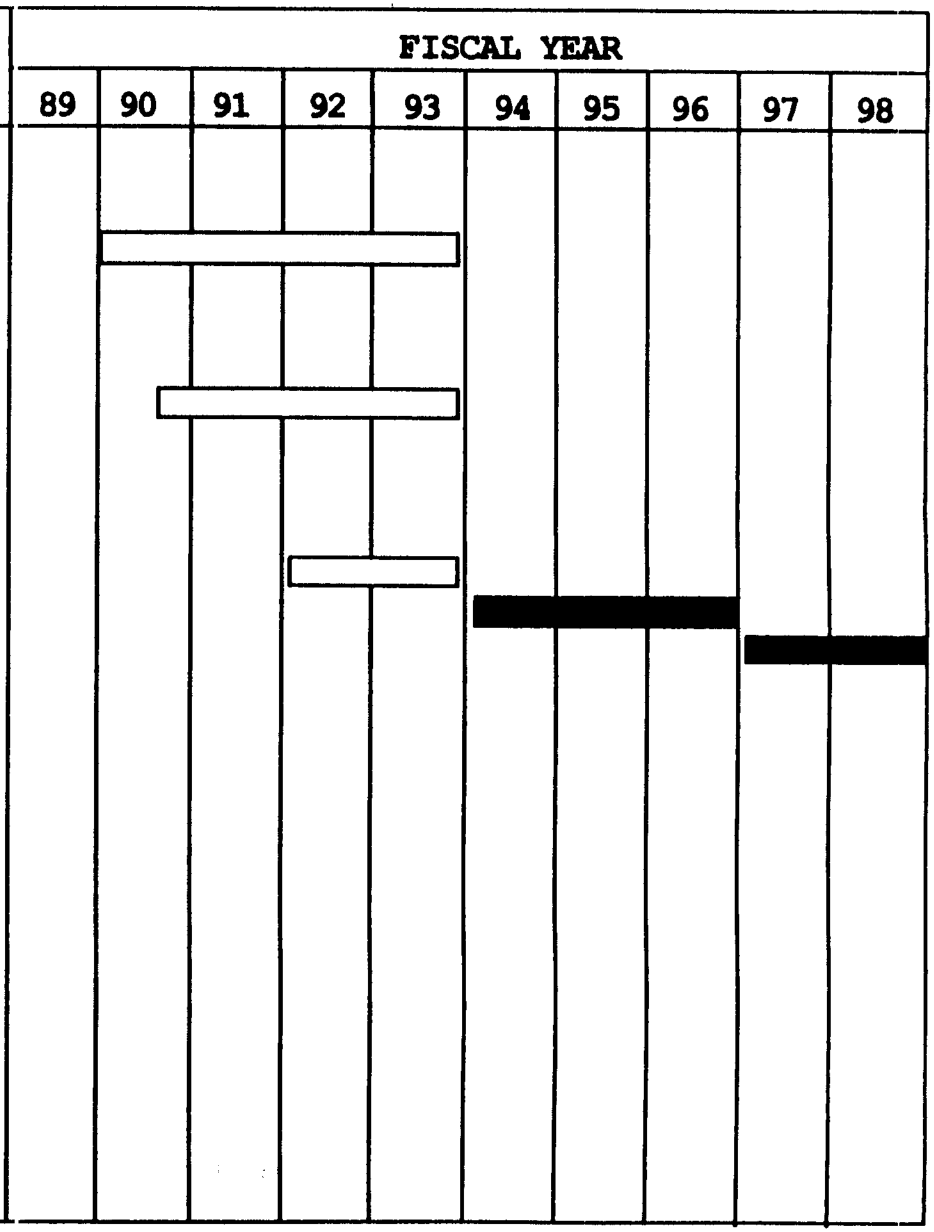


Figure 2.6.5-1

Figure 2.6.5-2
System Tests
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.4.5.1 REQUIREMENTS					
• All Testing Needs Defined				Δ	
1.4.5.2 TEST FACILITY REVIEWS					
• Capability Assessments Complete					Δ
1.4.5.3 FLIGHT TESTS					
• Testing Needs Defined					Δ

2.6.6 Human-Rated Tests

2.6.6.1 Objectives

The overall objective of the Human-Rated Tests element is to evaluate the functional design and operation of each mission-specific P/C CLLS system developed and design during the course of the project. The necessary tests must be conducted to the extent possible, under the conditions and with the system demands that resemble real-use environments. Thus, testing will be required on the ground and in space for subsystems containing gravity-, acceleration-, or radiation-dependent processes. Evaluations will be structured to generate data on integrated hardware operation, and to compare the data with previously established requirements with data obtained from breadboard tests and with design expectations. Data will be gathered on hardware operations at the process, subsystem, and system levels; on the interfaces between processes on subsystems and systems; and on the operation of control systems during nominal operations and when confronted with scheduled transients. It is also essential that the operation of all hardware be evaluated during randomly scheduled changes in operating parameters, such as power interrupts, temperature and mass flow fluctuations, control system interrupts, or interface perturbations.

Since the P/C CLLS systems that will be developed to meet the requirements of long-duration missions are expected to be relatively complex, the hardware testing can be expected to pass through a series of phases. The first phase will be the testing of individual subsystem designs using the actual hardware that is under development for the specific mission. The next phase will involve ground-based tests of complete, mission-hardware-based P/C CLLS systems. These tests will be full-scale in scope and will evolve from the use of simulated crews to evaluations conducted in the presence of "real" manned crews.

Within the context of this five-year plan, the initial objective of the Human-Rated Tests element will be the development of testing requirements. This effort to develop requirements will begin late in the five-year period covered by this project plan. Planning and developing requirements for these ground-based tests must, of necessity, await the completion of at least preliminary design for the P/C CLLS subsystems and the integrated, mission-specific systems. Adjustments in this timing may occur in response to the progress achieved under the various P/C technical elements covered by this project plan.

Flight experiments and tests will be important adjuncts to ground-based testing. Planning for these tests is also one of the objectives of the Human-Rated Tests element.

2.6.6.2 Technical Approach

The approaches to hardware testing on the ground and in space, have been developed by NASA over the past 25 years. These approaches have been documented both formally and informally, and will be followed. Documentation describing previous life support subsystem and system test activities will be used to design specific tests and to conduct evaluations of mission-specific hardware. These designs of tests and evaluations must take particular note of the complexities which are inherent in an integrated P/C CLLS system.

The Work Breakdown Structure for the Human-Rated Tests element is composed of the following three sub-elements:

1.4.6.1 Requirements
1.4.6.2 Ground Test Bed
1.4.6.3 Flight Experiments

Of the above sub-elements, only the Requirements sub-element will receive attention in the five years covered by this project plan.

2.6.6.3 Description

REQUIREMENTS (WBS 1.4.6.1)

The tests of integrated P/C CLLS systems to be conducted under the Human-Rated Tests element will require the presence of an adequate ground-based test bed facility. The planning process to be addressed under this sub-element will focus on the development of testing requirements that must be met by this ground-based test bed. The evolving designs for integrated, mission-specific P/C CLLS systems will be reviewed to define these requirements. This review is expected to begin at the start of FY93 and continue onward to FY96 when actual testing will begin.

GROUND TEST BED (WBS 1.4.6.2)

The work conducted under this sub-element is that of the actual testing operations. These tests are expected to begin in FY96 and continue beyond FY98.

FLIGHT EXPERIMENTS (WBS 1.4.6.3)

Planning for these experiments will evolve during the later stages of defining the requirements for the ground-based test bed. These flight experiments are expected to occur during the post-FY99 time frame.

2.6.6.4 Schedule

See Figure 2.6.6-1.

2.6.6.5 Milestones/Deliverables

See Figure 2.6.6-2

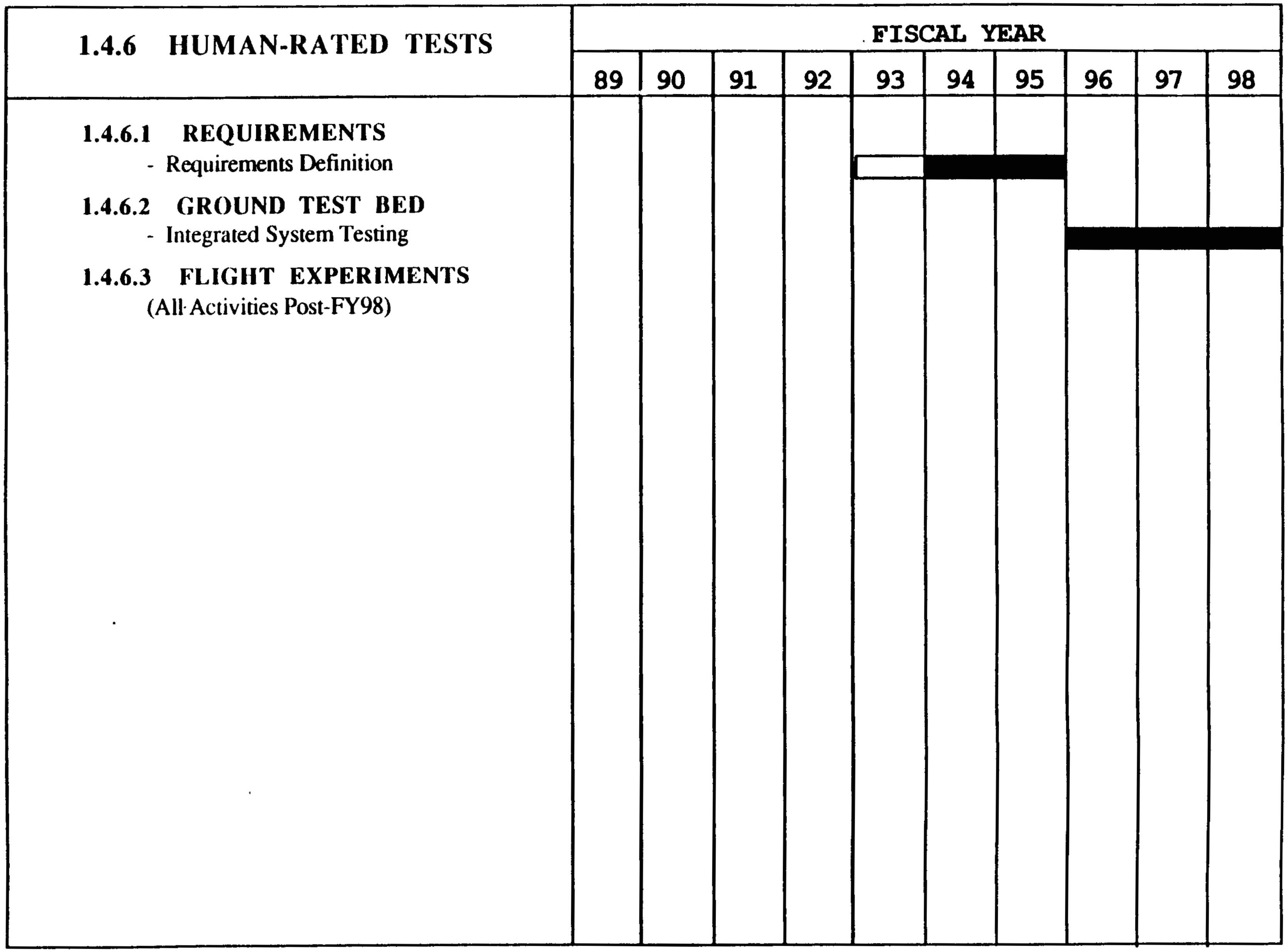

1.4.6 HUMAN-RATED TESTS
FISCAL YEAR
89
90
91
92
93
94
95
96
97
98
1.4.6.1 REQUIREMENTS
- Requirements Definition
1.4.6.2 GROUND TEST BED
- Integrated System Testing
1.4.6.3 FLIGHT EXPERIMENTS
(All Activities Post-FY98)

Figure 2.6.6-1

Figure 2.6.6-2

Human-Rated Tests

Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.4.6.1 REQUIREMENTS • Planning Initiated (All Other Milestones Post-FY93)					Δ
1.4.6.2 GROUND TEST BED (All Milestones Post-FY93)					
1.4.6.3 FLIGHT TESTS (All Milestones Post-FY93)					

2.7 FIVE YEAR PLANNING SUMMARY

2.7.1 Fiscal Year 1989 Schedule

Figures 2.7.1-1 summarize the scheduled FY89 activities for each of the P/C CLLS technical elements. Activities for Portable Life Support Systems (WBS 1.2) are not included in these schedules.

2.7.2 Five Year Schedule

Figures 2.7.2-1a, 2.7.2-1b and 2.7.2-1c summarize the principal areas of effort in the FY89 through FY93 period for each of the P/C CLLS technical elements. Again, activities for Portable Life Support Systems (WBS 1.2) are not included in these summaries.

2.7.3 Major Milestones/Deliverables

See Figure 2.7.3-1.

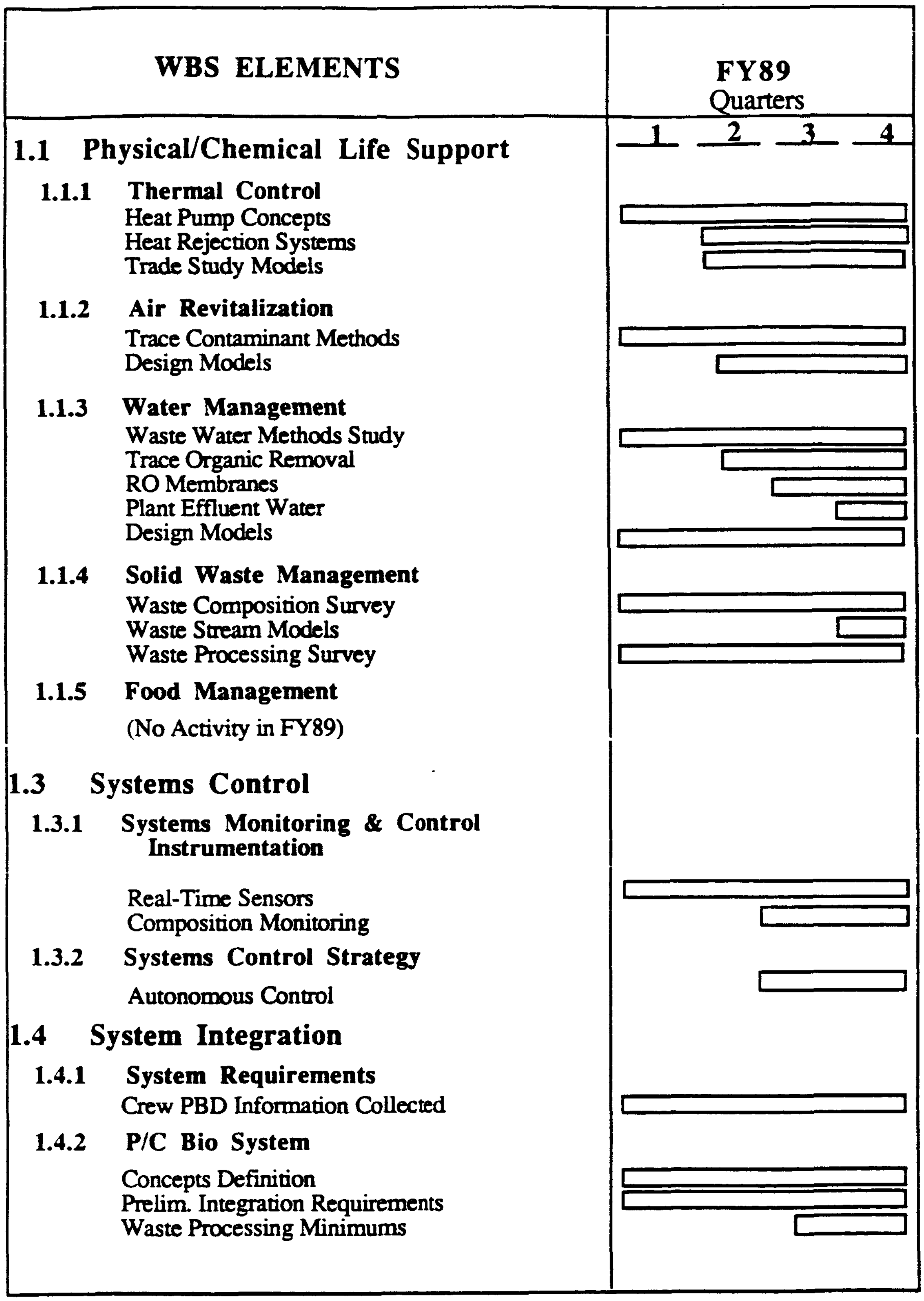

WBS ELEMENTS
FY89
Quarters
1
2
3
4
1.1 Physical/Chemical Life Support
1.1.1 Thermal Control
Heat Pump Concepts
Heat Rejection Systems
Trade Study Models
1.1.2 Air Revitalization
Trace Contaminant Methods
Design Models
1.1.3 Water Management
Waste Water Methods Study
Trace Organic Removal
RO Membranes
Plant Effluent Water
Design Models
1.1.4 Solid Waste Management
Waste Composition Survey
Waste Stream Models
Waste Processing Survey
1.1.5 Food Management
(No Activity in FY89)
1.3 Systems Control
1.3.1 Systems Monitoring & Control Instrumentation
Real-Time Sensors
Composition Monitoring
1.3.2 Systems Control Strategy
Autonomous Control
1.4 System Integration
1.4.1 System Requirements
Crew PBD Information Collected
1.4.2 P/C Bio System
Concepts Definition
Prelim. Integration Requirements
Waste Processing Minimums

Figure 2.7.1-1

WBS ELEMENTS		FY89 Quarters 1	2	3	4
1.4.3	**System Analysis & Assessment**				
	Modeling Plans Survey				
	Technology Assessments				
1.4.4	**Validation & Verification**				
	Initial Validation Strategy				
1.4.5	**System Tests**				
	(No Activity in FY89)				
1.4.6	**Human-Rated Tests**				
	(No Activity in FY89)				

Figure 2.7.1-1 (continued)

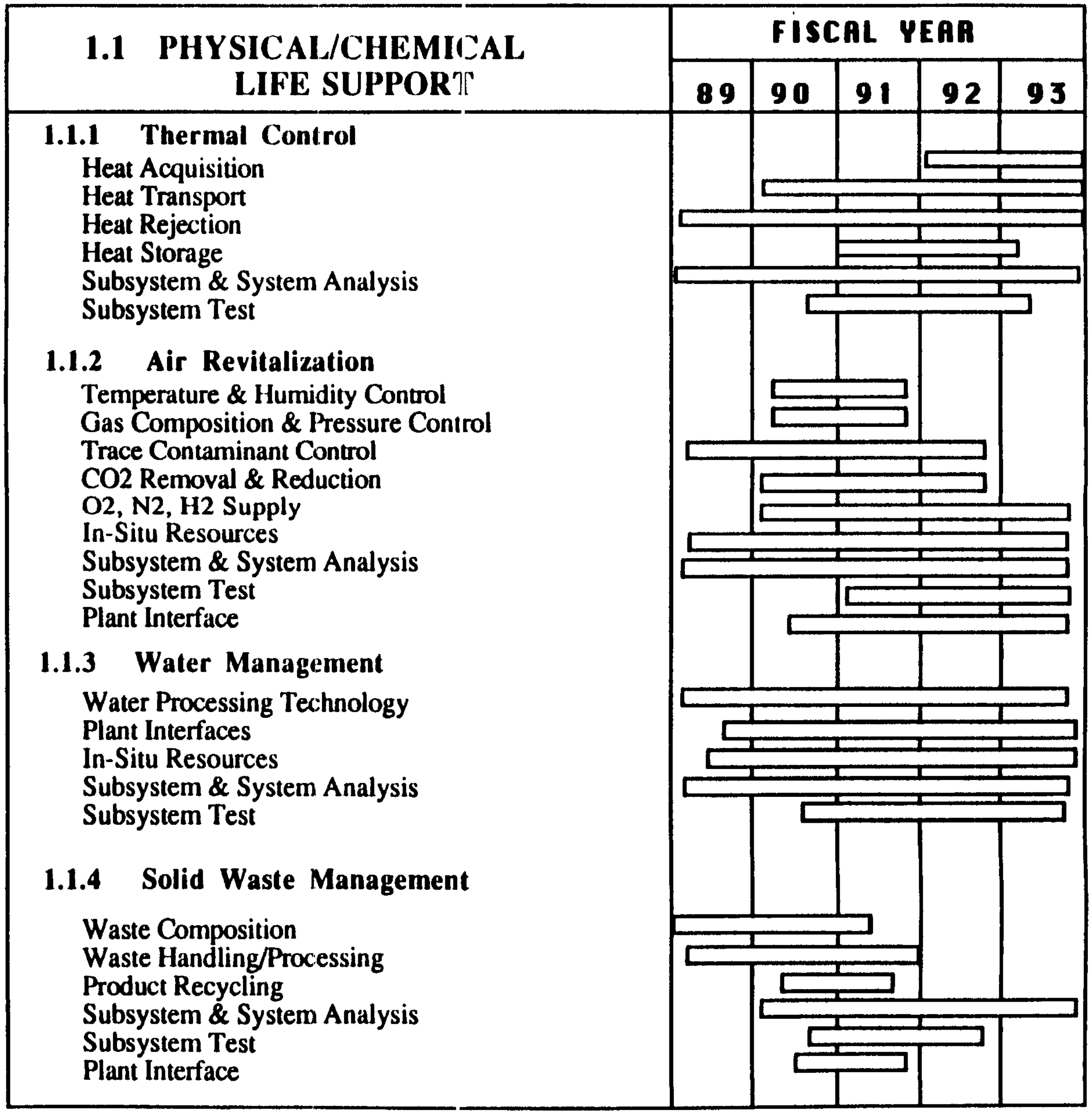


Figure 2.7.2-1 a.

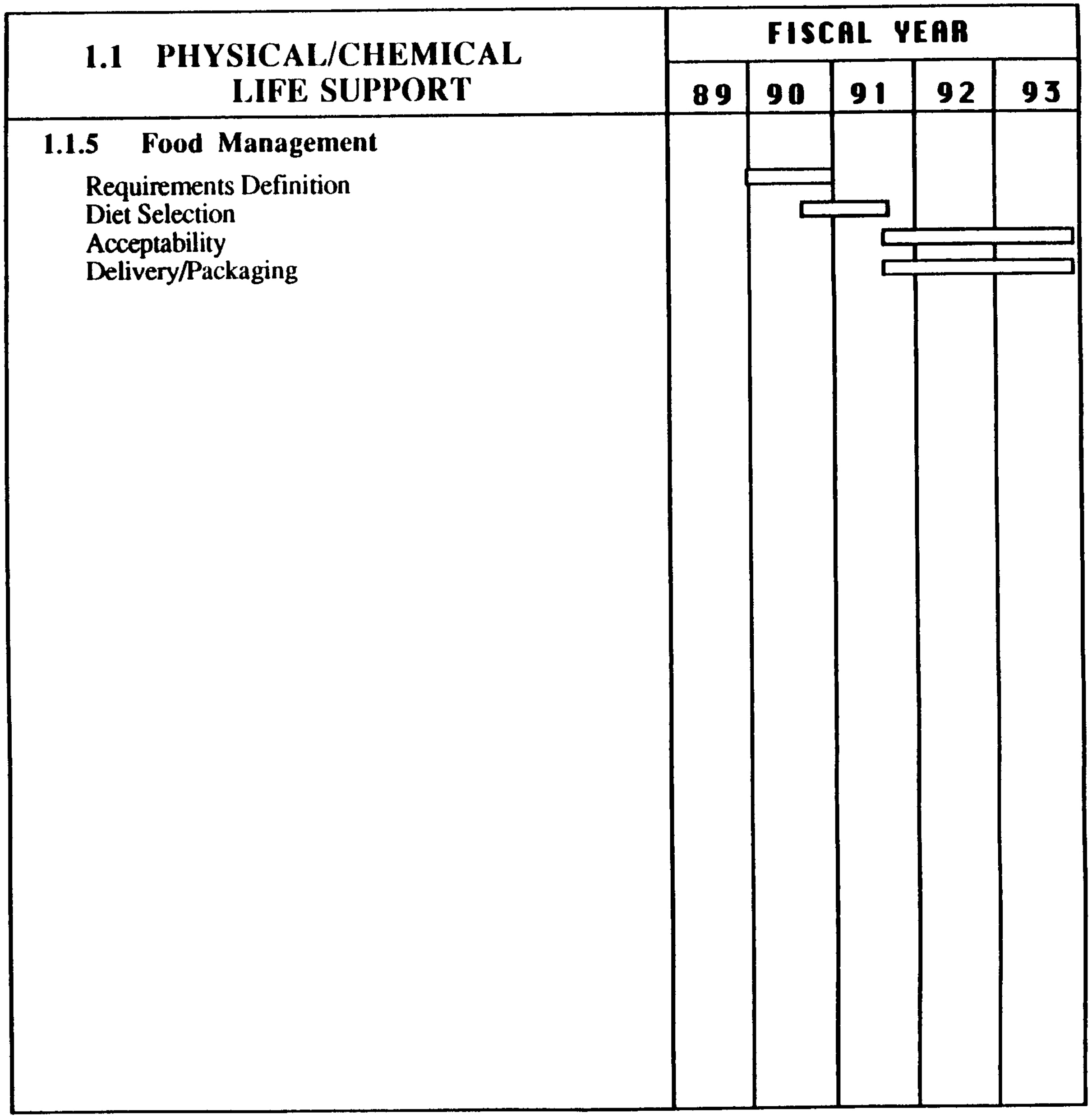


Figure 2.7 2-1 a. (continued)

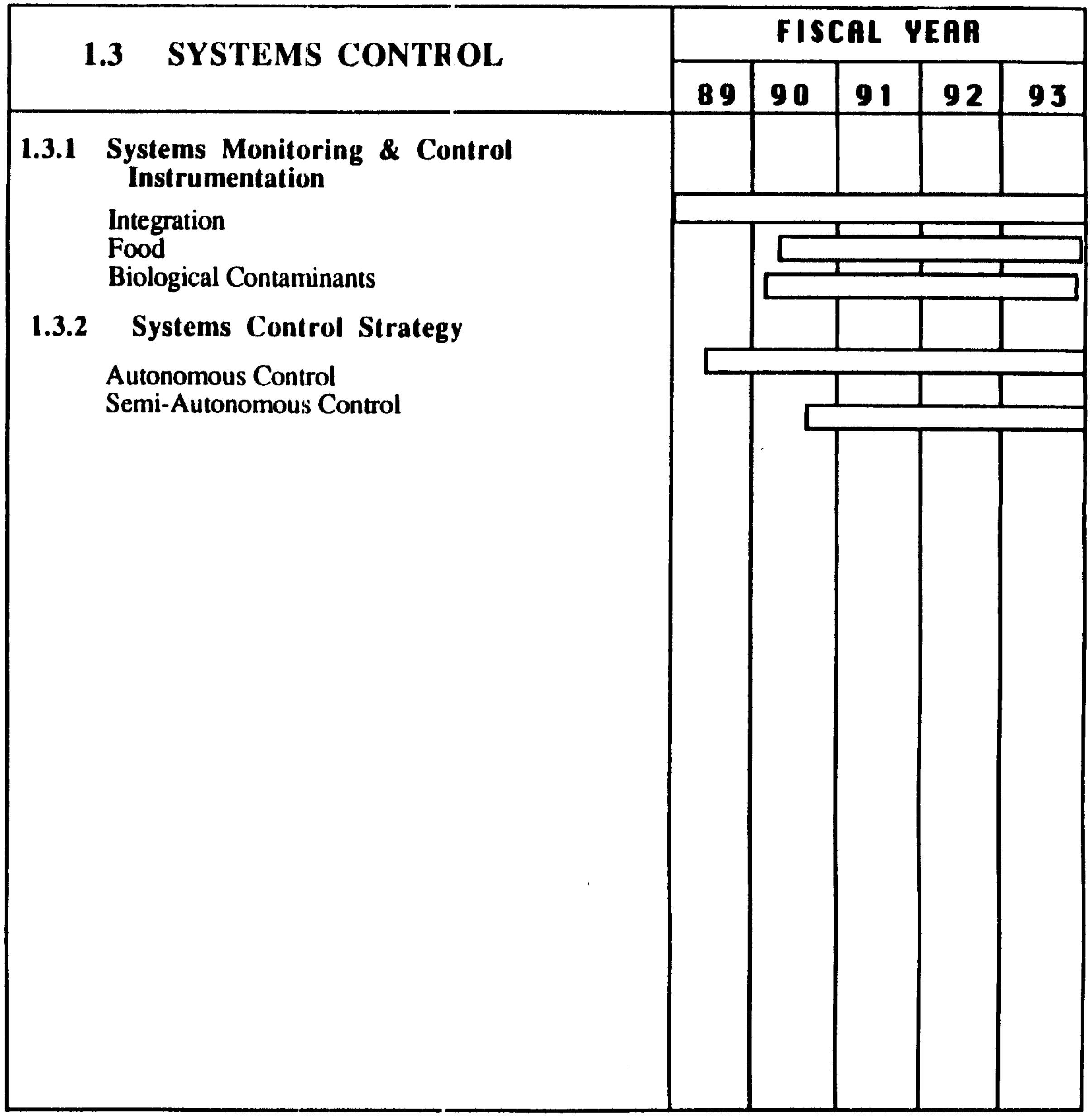


Figure 2.7.2-1 b.

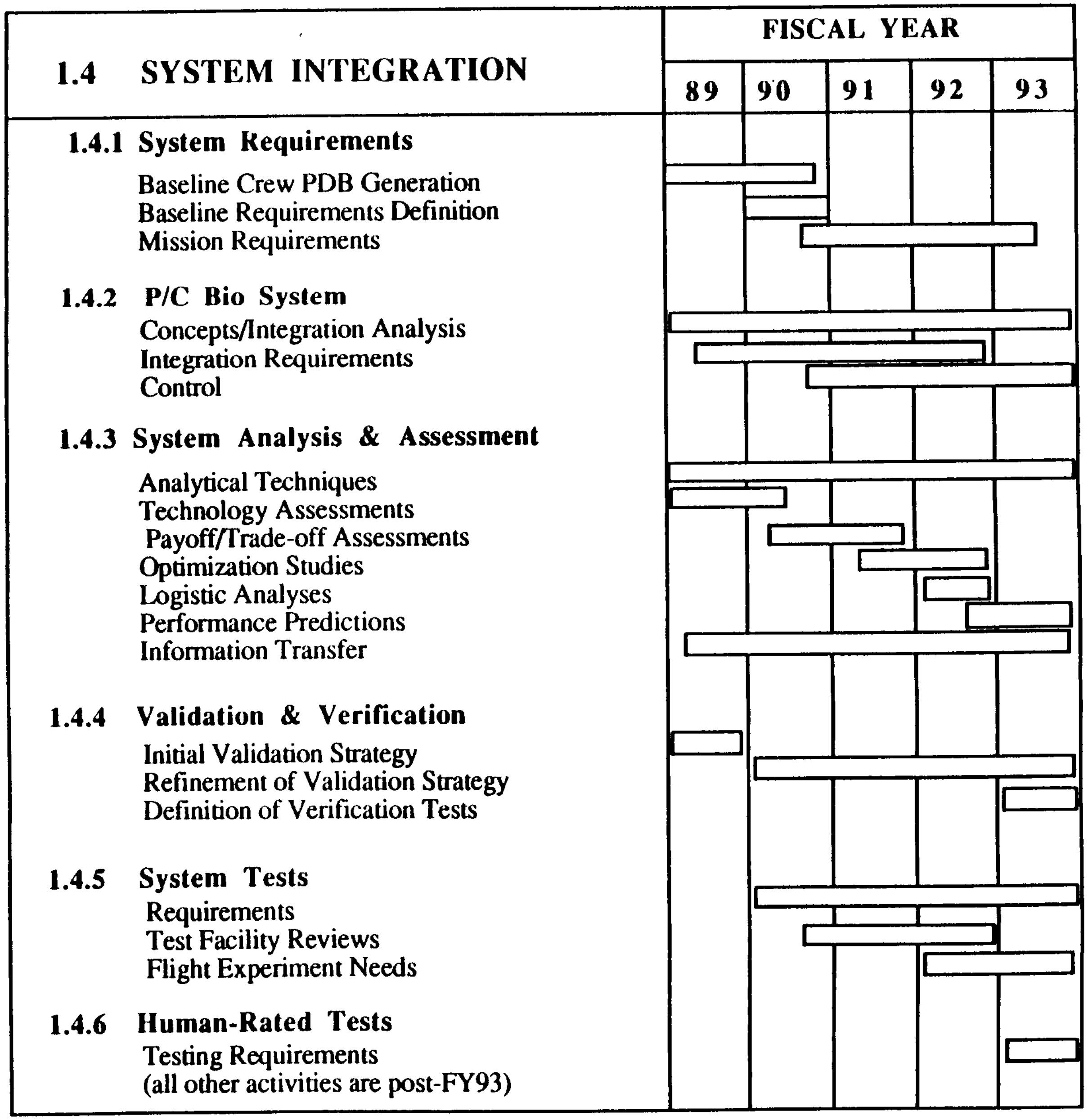


Figure 2.7.2-1 c.

Figure 2.7.3-1
Five Year Planning Summary
Major Milestones/Deliverables

Project Element	*89*	*90*	*91*	*92*	*93*
1.1 PHYSICAL/CHEMICAL LIFE SUPPORT					
• Technology Surveys Completed			Δ		
• Key Experiments Completed				Δ	
• Subsystem Designs Complete				Δ	
• Design Packages Complete					Δ
1.3 SYSTEMS CONTROL					
• Integration Designs Complete				Δ	
• Control Strategies Defined					Δ
1.4 SYSTEM INTEGRATION					
• Baseline Requirements Defined		Δ			
• Mission Requirements Defined				Δ	
• Hybrid System Design Complete					Δ
• Trade-off Studies Complete			Δ		
• Optimization Studies Complete				Δ	
• Validation Methods Defined				Δ	

2.8 PROCUREMENT STRATEGY

Several classes of procurement action will be required during the course of the work for the P/C CLLS project. The principal procurement actions can be categorized as those necessary to carry out routine R & D tasks in-house and the potential need to both expand facilities and contract for outside work.

Contracting plans are described in Section 3.0 of this project plan. With respect to ARC, the services of an on-site support contractor will be procured through preparation of a Request For Proposals (RFP) and competive bidding to supply the required skills. It is anticipated that the other participating NASA centers will either follow this same approach to engaging support contractor services or acquire the necessary support personnel through contracts already in-place.

R & D tasks may also be contracted to private industry and/or universities as a means of accomplishing some of the work described for the technical elements contained in this project plan. Contracts with industry will be initiated primarily through competitive bidding involving preparation of RFPs and accompanying statements of Work (SOWs). Occasional sole source procurements may be employed where appropriate. University R & D will be procured primarily through use of Joint Research Interchanges (JRIs). Some R & D results also may accrue to the P/C CLLS Project through the Small Business Innovative Research (SBIR) program.

ADP and conventional laboratory supplies will be required during the first five years of the project as described in this plan. The ADP procurements will be planned and implemented in accord with NASA's Information Technology and Services (ITS) plan. This plan is updated annually throughout NASA. Conventional laboratory supplies will be purchased within the P/C CLLS project as required by the applicable technical element.

Facilities plans are described in Section 4.0 of this project plan. A facilities assessment will be conducted in FY89. This assessment will include the definition of required purchases of acquisitions of major laboratory equipment. All of the participating NASA centers will be covered by this assessment.

2.9 LONG RANGE PLAN

All critical physical/chemical technologies providing for an automated and efficient P/C CLLS system will be thoroughly tested at the subsystem and integrated system level. Research-oriented tests of breadboard prototypes and partial subsystems will be conducted in facilities that are found to be suitable through assessments which match needs with capabilities. Tests of full subsystems and integrated, mission-specific P/C CLLS systems will then be performed in ground-based testbeds. These system-level tests will focus on evaluation of designs suitable for supporting the long duration manned missions to be defined by OEXP. These testing activities will occur during the years 1993 and 1998. Safety and reliability will be assured through development of fault-tolerant system diagnostics and controls. Validated mathematical models of the integrated subsystems will be developed and available to serve as the basis for the development of operational models for system development and mission execution. After 1997, crew-rated full-scale system ground tests will begin for final validation of integrated system operation and model verification. The concept definition and requirements of a first-generation combined physical/chemical-biological closed-loop system will be defined during the 1993 and 1998 time frame. Flight tests of P/C CLLS hardware will take place in the post-1999 timeframe. A more detailed graphical diagram of this plan can be found in Section 1.8 (Figure 1.8-1) of this project plan.

3.0 CONTRACTING PLANS

3.1 OVERVIEW

Although NASA will develop and maintain the foremost expertise in P/C life support technologies, contracted efforts in support of the P/C CLLS Project will include industry, universities, and the Small Business Innovative Research (SBIR) Program as appropriate to enhance NASA in-house capabilities or to provide those capabilities not within the current or planned expertise of the agency. Groups under contract to the NASA centers will provide such services as research and technology development tasks in specific areas defined by NASA, support service contractors of a technical or administrative nature, and other services as appropriate.

NASA-ARC will release for competitive bid a Request For Proposals (RFP) for on-site support service contractors to augment skills at ARC. The ARC procurement office will administer the contract.

3.2 INDUSTRY

The expertise and computerized simulation techniques available within the aerospace and chemical processing industries will be utilized as well as the software and computer simulation industries to develop the analytical simulations of proposed P/C processes in addition to the actual process development, if potential benefit is feasible. SBIR procurements will also be encouraged as a means of developing novel and potentially beneficial life support technologies. A close working relationship will be encouraged with aerospace companies who will ultimately build the closed-loop system.

3.3 UNIVERSITIES

Another means of accomplishing basic research and technology development for life support is through the use of university grants in areas which may have potential benefit to closing the life support functions. University involvement will be encouraged and regular reviews of NASA-funded grants in P/C CLLS technologies will be held to highlight academic research and promote a free exchange of technology ideas among the life support research community.

Implementation of an institute formed with a reknown university for the purpose of advancing life support technology will be explored, and initiated if appropriate. Communication, coordination, and cooperation will be established and maintained between CLLS Project participants and the University Space Engineering Research Centers (USERC), as appropriate.

4.0 FACILITIES PLANS

4.1 OVERVIEW

Research work for the P/C CLLS project will require laboratories and computing facilities as well as capabilities for testing subsystems and mission-specific, integrated systems. The primary areas of activity in FY89 through FY93 will be computer modeling and simulation of subsystems and integrated systems with emphasis on the preparation of design packages. Major laboratory-scale studies will also be conducted during this period.

System tests will begin in FY94 and continue on through FY99. These tests will commence with component and breadboard evaluations in research test facilities. Full-scale test of mission-specific, integrated P/C CLLS systems in human-rated ground test beds are expected to begin in FY98.

Planning efforts will be necessary to insure that adequate laboratory, computing and testing facilities will be available when required to meet the long-term project schedule. Assessments of existing facilities at all participating NASA Centers will be performed at an early stage in the planning process. These assessments will provide input for developing an overall facilities plan for the P/C CLLS project.

4.2 LABORATORIES AND COMPUTING

Existing laboratories and computing facilities are believed to be adequate to support the P/C CLLS project during the early years. However some upgrading and expansion of laboratories and addition of mini- and micro- computing facilities will be necessary in the future. Assessments of existing laboratory and computing facilities will be performed to develop the scope and timetable for these future expansions and additions.

4.3 DEMONSTRATION AND TESTING FACILITIES

Specific requirements for demonstration and testing facilities must be evaluated through a detailed assessment. It is anticipated that facilities will be required in FY91 and beyond for integration and testing of P/C CLLS processes and components at the breadboard prototype and partial subsystem levels. The purpose of these tests will be to provide data that will guide the R & D effort. Full-scale testing of integrated, mission-specific P/C CLLS systems will require human-rated, ground-based test beds. This type of facility will be necessary in FY98 and beyond. Existing demonstration and testing facilities at all of the participating NASA centers will be examined with respect to meeting the foregoing future needs.

4.4 FACILITIES ASSESSMENT

In FY89, the project management will conduct a facilities assessment to insure that adequate facilities will be in-place and operational when required. This assessment will examine the available facilities and anticipated requirements at each of the participating NASA Centers (ARC, JPL, JSC, LaRC and MSFC). An examination of the projected demands on existing facilities will be made along with an identification of potential future needs. The assessment will address the full range of computing, laboratory, engineering development and test facilities required for the P/C CLLS project.

The results of the facilities assessment will be used to develop an overall facilities plan for the P/C CLLS project. This plan will define any new facilities that may be needed in the future and identify the appropriate activities to be pursued to build or acquire them. The overall facilities plan will be presented, reviewed and discussed at meetings of the Intercenter Working Group (See Section 2.2.2.3).

5.0 IN-SPACE RESEARCH AND TECHNOLOGY

Reliability of the life support system is crucial for the success of any human venture into space. Consequently, if there exists any doubt about the influence of gravity or any other factors unique to the space environment on the operation of critical part(s) of a life support system then flight experiments with the part in question must be carried out. These experiments must be carried out in the relevant environment and prior to the time a human becomes dependent for life support on the part in question. These experiments must be performed for a sufficient number of times and duration to eliminate any uncertainties regarding the influence of the space environment on part performance. Throughout the lifetime of this project the influence of gravity and the space environment in general on life support parts will be taken into consideration and when necessary flight experiments will be identified and carried out.

6.0 TECHNOLOGY TRANSFER PLANNING

Technology transfer among participating centers, universities, and industry is the responsibility of the P/C CLLS Program and Project Managers. Initially, the Intercenter Working Group (see section 2.2.2.3 of this document) will facilitate technology transfer among the NASA centers. Early in the project, efforts will be focused toward building a strong partnership with industry. Papers on P/C CLLS technologies and system designs will be presented at the annual Intersociety Conference on Environmental Systems (ICES). Both the ICES and the AIAA Committee on Life Support will be invited to participate in and co-sponsor a yearly symposium for promotion of Advanced Life Support information exchanges between NASA, universities and industry. Efforts will also be made to expand the publication of life support-related papers in peer-review journals published by professional societies such as the American Institute of Chemical Engineers (AIChE) and the American Chemical Society (ACS).

The key to successful technology transfer is a continuing, well-integrated effort throughout the project lifetime. Ideas for technology transfer mechanisms must be solicited, funded, and implemented. Technology transfer planning will be developed in greater detail in FY89 and 90.

7.0 SAFETY, RELIABILITY, MAINTAINABILITY AND QUALITY ASSURANCE (SRM&QA)

The ultimate reliance of the safety and well being of humans on the performance of a space borne life support system and the dependence of this system for accomplishment of mission objectives is well recognized. Thus, system safety and operational reliability define a major design constraint for the P/C CLLS project. The following SRM&QA program will be undertaken to address these constraints.

SRM&QA

SRM&QA is the application of engineering and management principles, criteria, and techniques to optimize SRM&QA within the constraints of operational effectiveness, time, and cost throughout all phases of the system life cycle.

The overall purpose of the SRM&QA program will be to identify applicable NASA/ARC requirements for developing and implementing a support program of sufficient comprehensiveness:

1) To identify the hazards of a system and to impose design requirements and management controls to prevent mishaps by eliminating hazards or reducing the associated risk to a level acceptable to the NASA/ARC managing authority;

2) To ensure that a system will perform its function for a specified period of time, utilizing such standard reliability and maintainability techniques as fault tree analysis, failure modes and effects analysis, mean time between failure analysis, and reliability modeling; and

3) To monitor the preparation of procurement specifications, conduct source surveys of potential suppliers, monitor supplier performance through inspection of incoming prototype hardware against design drawings.

The SRM&QA will be implemented as a part of the process of moving mission-specific, integrated P/C CLLS system designs from the R & D phase to the prototype hardware testing phase.

8.0 CONTROLLED ITEMS

For purposes of this research, Controlled Items refer to proprietary technologies, including leased computer codes developed by universities or industry, which may be required for achieving critical P/C CELSS objectives. Any such controlled item will be identified and any necessary contractual provisions specified.